Wind and Doppler Shift Compensation for Spread Spectrum Sound-based Positioning System(Digest_要約)

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Thesis

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Chapter 1

General Introduction

1.1. Background

Automation/robotic system and precision agriculture hold an important role on shaping the future agricultural practices. Automation/robotic systems have been intensively studied over last few decades. It has been applied in various agricultural operations such as weeding [1, 2], plant monitoring [3], application of fertilizer and chemicals [4], and harvesting [5-7]. Although it is still considered as a tough job to bring it into a real commercial applications, there is a strong driving factor that still makes it an important research area that attract a great attention from many researchers. Recently, the lack of workforce has become a major issue in agriculture, especially in developed countries. There is an increasing of number of farmer that entering aging stage and in the other hand there is a decreasing of interest of young generation to get involved in such agricultural activities. Automation and robotic system are expected to be a potential solution to solve this problem.

There is also an emergence and a rising concern on the practice of precision agriculture observed in the recent years. Such kind of phenomena is mainly driven by a demand to develop such a profitable agricultural operation. Agriculture is no longer considered just as part of tradition/culture for fulfilling the daily needs. It has transformed into industry where profitability is an important issue. Precision agriculture is also considered as one of key components for attaining sustainable agriculture, a concept that try to keep the balance of maximizing crop productivity and maintaining economic stability, while minimizing the utilization of finite natural resources and minimizing negative environmental impacts [8].

Along with the increasing of interest on robotic/automation as well as on precision agriculture, there is also a demand to develop the required supporting technologies. One of them is development of positioning system. There are many applications that require position information such as application of Site Specific Crop Management (SSCM) for precision agriculture [9-10] and development of navigation system of autonomous vehicles [11-14].

For many applications, Global Positioning System (GPS) is the most widely adopted technology. Figure 1.1 illustrates application of GPS for supporting various agricultural operations such as soil monitoring, application of fertilizers and pesticides, plant scouting, yield mapping, guidance system of autonomous combine harvester and so on. Generally, GPS can provide high positioning accuracy especially when real-time kinematics (RTK-GPS) is used. Typically it can provide position information within few centimeters accuracy. However there are some limitations. For GPS with high accuracy which is required in many applications, it is relatively expensive and in certain condition it cannot provide position information due to the absence of signal. The high cost of GPS is considered as one of main problem. From previous reports that tried to conduct economic analysis of precision agriculture practices [8, 9] and autonomous vehicle operation [15,16], it indicated that the positioning system (i.e. GPS) is one of main contributor of the total development cost. Therefore it is a demand to develop a new alternative low-cost positioning system. If it can be done, such cost reduction will give significant contribution to accelerate adoption and realization of precision agriculture as well as automation/robotic system. Such kind of system is very suitable especially for Asian style farming which is typically applied intensive farming concept in relatively small area.

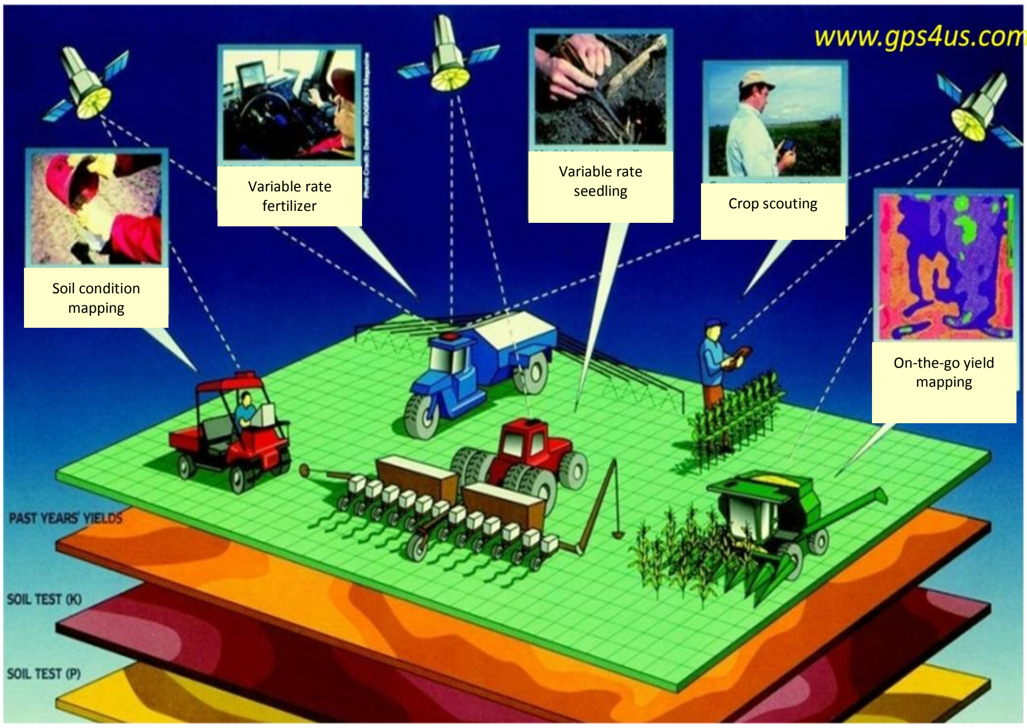

Figure 1.1. Utilization of GPS in various agricultural operations. (*source: gps4us.com*)

There are many reports about development of alternative positioning system especially for indoor environment by using various technologies such as infrared (IR), ultrasound, radio-frequency identification (RFID), wireless local area network (WLAN), ultra-wideband (UWB), magnetic field, laser, machine vision and audible sound. Each of those technologies has special characteristic that needs to be considered when selecting the most appropriate one for certain application. Some of infrared systems offer very high accuracy (several millimeters) for room size area, however it also some limitations such as interference from fluorescent light and sunlight. Ultrasound based positioning system is also widely adopted. It can provide high accuracy (several centimeters), convenient to use because it is non-audible and inexpensive. However, there are some limitations. It suffers from reflection and also interference of other noises. For one who interested to know further, there are some articles that give more comprehensive review on those alternative positioning systems [17-19].

In recent work, we try to develop an alternative positioning system in agricultural area for supporting some operations such as navigation of weeding robot. Among of those available technologies, sound-based local positioning system is considered as a good alternative for this purpose. It can provide high positioning accuracy and also can be developed in relatively low cost. Some components of such kind of system (e.g. speaker, microphone, amplifier) have been used in the audio market for many years; are readily available, inexpensive and reliable [20]. Also, unlike other technologies that suffering of non-line-of-sight (NLOS) condition, sound wave is more tolerant especially by using low frequency wave [21].

More specific, we consider for using spread spectrum sound. There are a number of characteristics that recommend such an approach for this application. It has high noise tolerance, as well as high signal identification properties [22]. Also, as mentioned in [23], due to the large bandwidth and continuous nature of the spread spectrum approach, high measurement accuracy can be achieved using this kind of system. To date, this approach has been successfully applied to non-agricultural settings [24-27]. In the current research, we try to optimize the system to an agricultural setting, where conditions are substantially different from previous applications. Figure 1.2 shows the overview of the aimed positioning system. There are many factors that need to be taken into account to obtain high positioning accuracy such as temperature gradient, wind, background noise, and the presence of obstacles. It is also a demand to make the proposed system easy to deploy and high scalability. This work tries to address some of those issues.

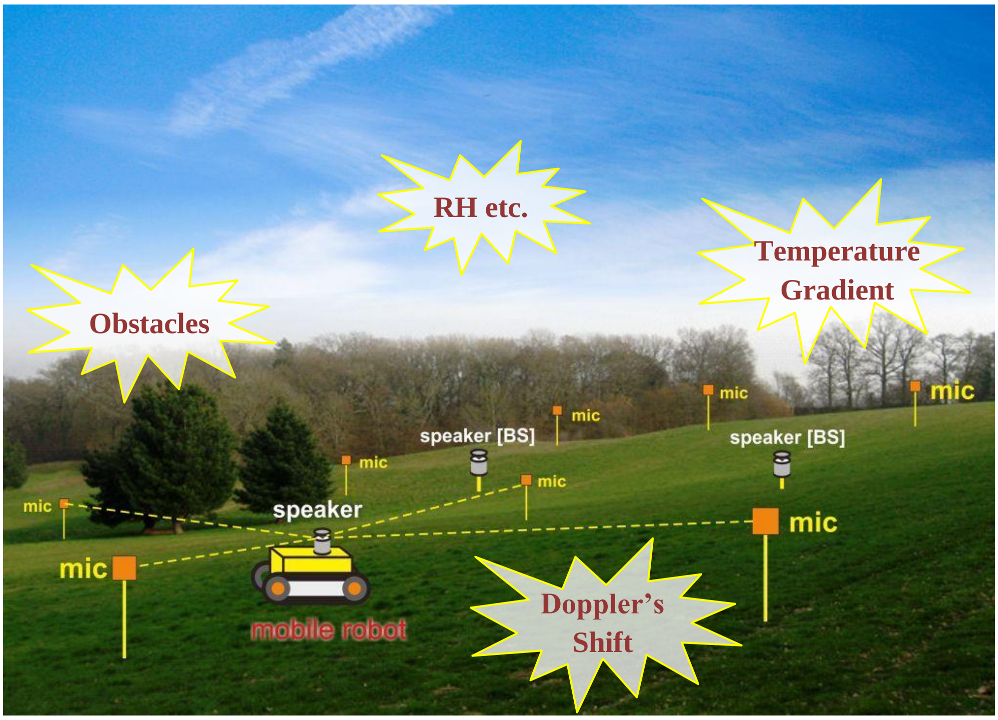

Figure 1.2. Overview of the proposed system.

1.2. Problem Statement

Agricultural area owns a special characteristic. There is high uncertainty and variability that makes adoption of certain technology into agricultural area without a proper adjustment is sometime difficult. For example, robotic systems have been widely adopted in some industries such as automotive, electronics, and food. However there is only limited commercial application of robotic system in agriculture (e.g. application in fruit grading facilities).

Similarly, although there is a promising potential of the use sound-based positioning system in agricultural area, there are some challenges need to be solved. There are many influencing factors that may interfere and give a negative influence on the performance of the positioning system such as temperature, humidity, noise and the presence of obstacles. Therefore development of such a system and compensation methods that capable of handling and minimizing the influence from those factors is highly required. Another issue is also arising when the positioning system is used to estimate the position of a moving object (e.g. in case of navigation of an autonomous vehicle). There is a problem corresponding to the presence of

Doppler's effect. The sound wave will experience a frequency shift that may decrease the performance of the positioning system.

Another issue is related to deployment of the system. To be easily accepted and adopted, setup of the system should be simple and easy. Otherwise it will be no interest to use the proposed system. Therefore development of self calibration system also becomes a main concern on the development of alternative positioning system [28-29]. Actually not only for purpose of easy use, self-calibration is also important to scale up the system. Typically, the coverage area of those aforementioned alternative positioning systems is much smaller than GPS. Therefore to enlarge the coverage area, those systems should be scaled up by using more devices. Here, such self-calibration plays the important role.

1.3. Research Objectives

In general, the main objective of this research is to develop an accurate sound-based positioning system in agricultural area. In this work accuracy of 100 mm is set as target. To achieve this objective, the negative influence of some factors that give performance degradation should be minimized by applying some compensation methods. As mentioned before, there are many influencing factor that should be taken into account. However, in this thesis we just focus on two important factors, wind and Doppler shift which is associated with localization of a moving object.

More detail, there are three objectives in this research: (1) to develop a compensation method for wind which is the main problem for outdoor application; (2) to develop a compensation method for Doppler shift problem which correspond to object movement. It is important for some applications with high mobility such as navigation of autonomous vehicle; (3) to develop an easy deployment method that make it easy to scale up the developed positioning system into wider area. In this case it is also important to put into account the developed compensation method. Therefore the developed method should use configuration that can accommodate both, self calibration and compensation for influencing factors.

1.4. Outline of the Thesis

Research topics covered in this thesis is depicted in Fig. 1.3. Overall, this work includes three parts: (1) The basic of the proposed sound-based positioning system; (2) Development of compensation method for wind and Doppler shift, two important influencing factors that may affect the positioning accuracy; and (3) First step attempt to scale up the proposed system into wider working area by introducing self-calibration method.

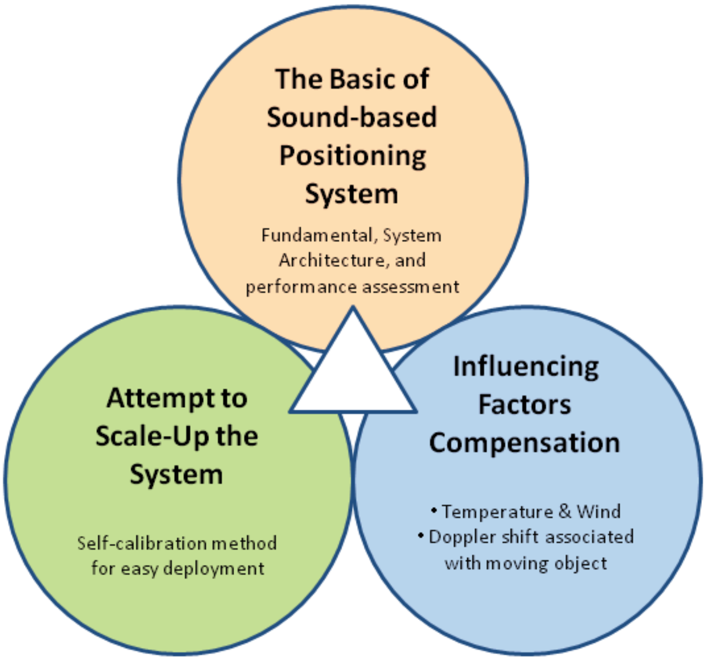

Figure 1.3. Outline of the thesis.

Chapter 2 gives general description of the proposed spread spectrum sound-based positioning system. It will cover, in brief, about fundamental of spread-spectrum sound as one of key components of the proposed system, methods for range measurement and three-dimension (3D) position estimation using the proposed system. Detailed hardware and system configuration are also discussed in this chapter.

Chapter 3 describes a wind compensation method by using base/reference station. Formulation of the proposed method as well as experimental result is reported here. It also discusses the influence of base station position and selection of multiple access technique on the wind compensation performance.

Chapter 4 describes an alternative method for compensating Doppler shift which is an important issue for position estimation of a moving object. Detail of the proposed compensation method and performance assessment is presented. Not only the influence of moving speed, but also the presence of additional influence from other factors (wind and noise) is also included in the performance assessment.

Chapter 5 explores the possibility to use self-calibration method for easy deployment of the proposed positioning system. It is can be considered as a first attempt to scale up the proposed system into wider area. The proposed self-calibration method was designed with consideration of previously mentioned compensation method especially wind compensation. Therefore, the proposed configuration not only accommodates self-calibration but also wind compensation.

Chapter 6 provides general discussions and overall conclusions of this thesis. This chapter also discusses some ideas for further improvement of the current system as well as some possible directions for further research, including some possible applications of the developed system.

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Chapter 2

Development of Spread Spectrum Sound-based Positioning System: fundamental, architecture and basic performance assessment

Abstract

This work tries to explore the use of spread spectrum sound to develop an accurate positioning system in agricultural area. This chapter gives a brief explanation of the developed spread spectrum sound-based positioning system which is used in the entire works in this thesis. This chapter begins with a brief description of spread spectrum sound, followed by methods of range measurement and position estimation, details of hardware and system configuration. Basic performance assessment in term of accuracy of range measurement as the basic data for position estimation is also presented.

2.1. Introduction

Nowadays, position information plays an important role in our daily life as people have become a more information-driven society [1]. Many devices equipped with positioning system such as GPS can be found easily e.g. car navigation system, mobile phone, etc. Such kind of trend also can be found in the agricultural activities, position information has been used in navigation of autonomous agricultural vehicle, monitoring soil properties, weed control, monitoring application of fertilizers and pesticides and so on [2-7].

In general, the advance development of GPS can fit that demand and has been widely adopted. However, there are some drawbacks. Although it works well for outdoor, it is hard to use it for indoor and also for certain environment due to the absence of signals from satellites. It is also quite expensive especially when high positioning accuracy is required. Hence, there are number of researches that try to find alternatives positioning system to address this issue.

They proposed various approaches using infrared (IR), ultrasound, radio-frequency identification (RFID), wireless local area network (WLAN), ultra-wideband (UWB), magnetic signals, laser, machine vision and audible sound. There are some articles that give review on those alternative positioning systems [8-10].

Among of those alternatives, system using sound waves offers some merits. It can provide comparatively high accuracy due to slower propagation speed compared to electromagnetic wave. It also can be developed at low cost because the required components such as speakers, microphones and amplifiers have been used in the audio market for many years; are readily available, inexpensive and reliable [11, 12].

In this work, we try to develop sound-based positioning system to support agricultural operation. Here, spread spectrum (SS) sound was used. As shown in the previous studies [13-16] such an approach could improve the robustness to the noises. Another advantage is the possibility to use Code Division Multiple Access (CDMA) technique, which can significantly reduce the time for acquiring data.

2.2. Ranging and Positioning Using Spread Spectrum Sound

There are several ways to localize an object by using sound wave. Among of them, trilateration or multilateration based on Time-of-Flight (TOF) of the sound wave sent from a transmitter to a receiver is the most widely used [17]. This approach is also used in this work. The following section describes the detail of spread spectrum sound, as well as methods for range measurement and also position estimation used in this work.

2.2.1. Generation of spread spectrum Sound

The spread spectrum signals are generated by using maximum length pseudorandom noise sequence (M-sequence) multiplied by carrier waves. Here, Binary Phase Shift Keying (BPSK) modulation was used.

Figure 2.1 illustrates the generation of spread spectrum sound. As the carrier, sine wave $s(n)$ as describe in the following equation was used:

$$s\,(n) = \sin\left(\frac{2\pi\, f_c}{f_s}\right) \times M(m) \tag{2.1}$$

with

$$m = round\left(\frac{f_c}{2f_s}n\right)$$

where f_c = frequency of carrier wave, f_s = sampling frequency and n = 0,1,2 … N-1 (N is the length of sample used for FFT calculation). The frequency of 24 kHz was used as carrier waves. Chip rate was set as 12 kcps (kilo chip per second), that means for each M-sequence was multiplied by two cycles of the carrier waves. Detail of the properties of spread spectrum sound used in this work is summarized in Table 2.1 and frequency property of the generated signal is shown in Fig. 2.2.

Table 2.1. Property of spread spectrum sound

Property	Value/Remark
Sampling frequency (f_s)	96 kHz
Sampling bit	16
M-sequence length	1023
Modulation	BPSK
Carrier wave frequency (f_c)	24 kHz
Chip rate	12 kcps

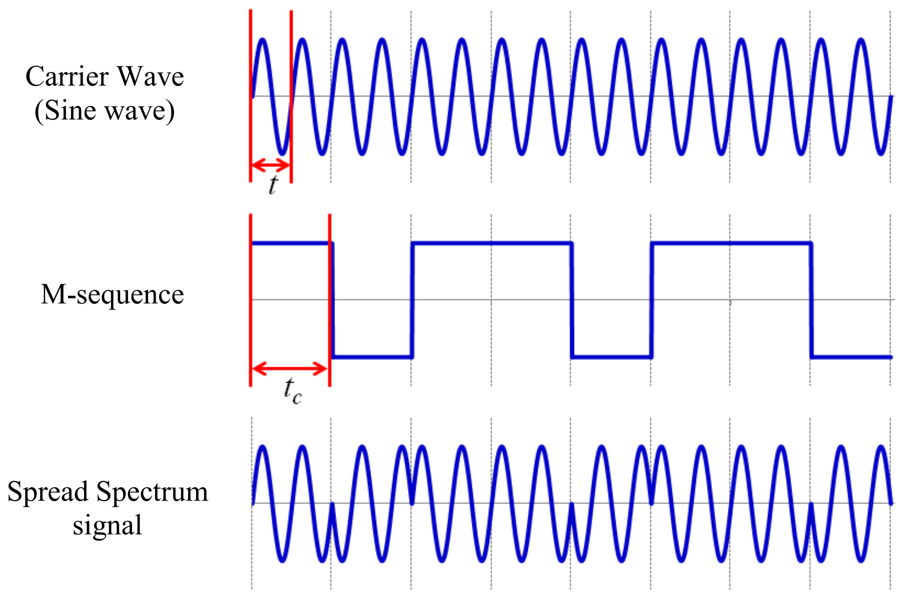

Figure 2.1. Generation of spread spectrum sound. (t=period of carrier wave, t_c=length of each M-sequence code).

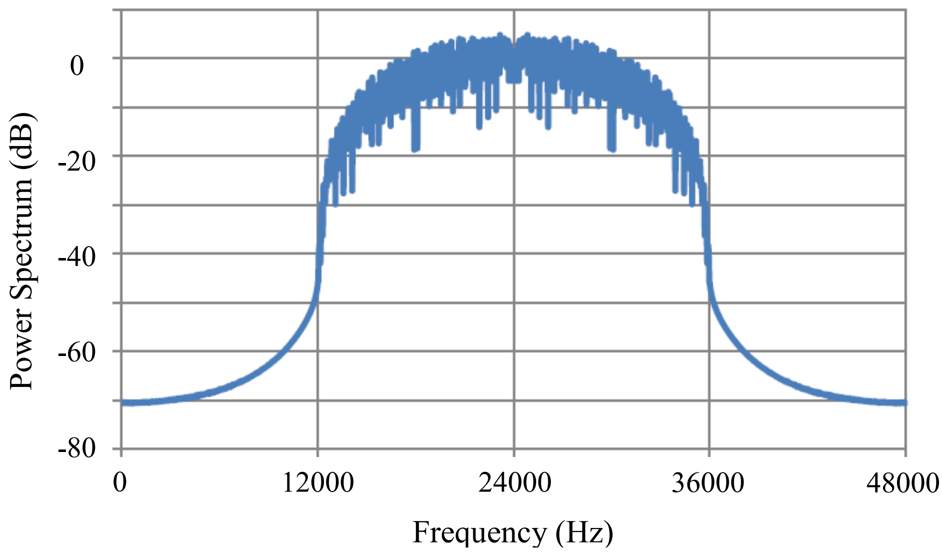

Figure 2.2. Frequency property of the generated spread spectrum sound.

Someone may wonder about the selection of the carrier wave which is 24 kHz. It is common to use ultrasound waves (>20 kHz) to generate non-audible sound in order to prevent additional noises. As shown in Fig. 2.2, some parts of the generated sound are in the range of audible sound which is potentially create noises and is in-convenient for users. It is actually deliberately selected based on some considerations.

The most important consideration is about background noise that may interfere and influence the performance. For practical use in agriculture, the influence of noise is un-avoidable. At least, it will be noises coming from the device/machine that utilize the sound-based positioning system itself. Hence, it is important to set the frequency of the sound wave far away from the range of frequency where the noises of operating machines present. To determine this range, we exercised the noises generated from various agricultural machineries operations as shown in Fig. 2.3.

From the results, it indicated that noises generated from the tested machines were in low frequency. Therefore, it is better to set the sound wave at higher frequency. However there is also another factor that needs to be considered. The lower frequency gives a great capability to reach long distance [18]. Low frequency wave is also less suffering of the presence of obstacles. In the other hand high frequency gives high accuracy. It is some kind of tradeoff. Considering these constrains, spread spectrum sound wave with center of carrier frequency of 24 kHz considered as a reasonable choice.

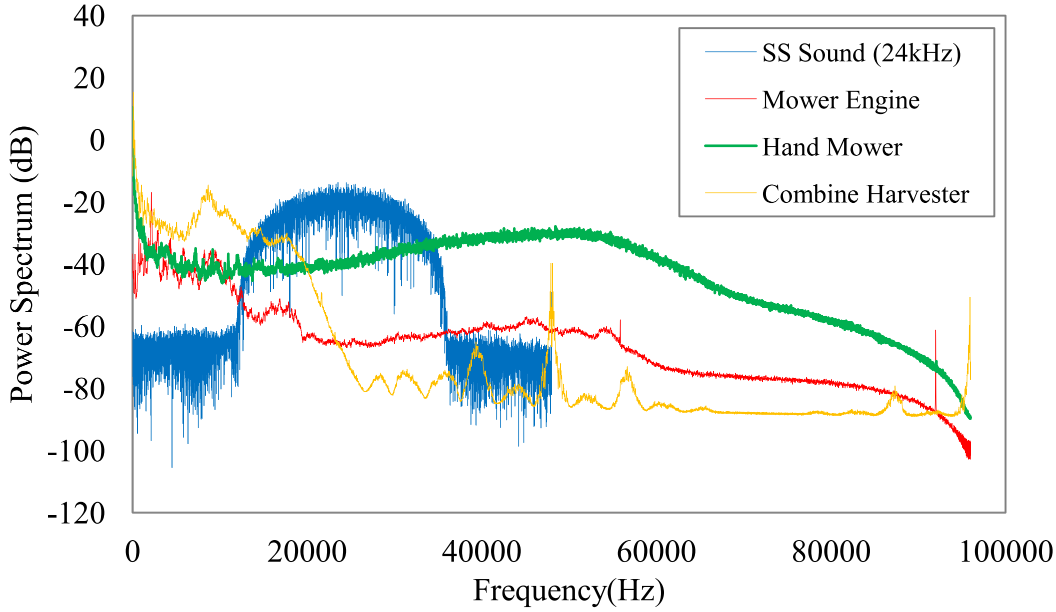

Figure 2.3. Frequency property of noises generated by various agricultural machineries.

2.2.2. Time of Flight (TOF) estimation and distance measurement

Like other sound-based system, to estimate the TOF, first the transmitter needs to send a trigger signal to the receiver as a command to start the timer. In the most cases, this trigger signal is sent by using radio frequency wave which has much higher speed than sound wave. After sending trigger signal, immediately, a predefined acoustic signal (sound) is sent and then is detected by the receiver. TOF is then estimated from the difference of arrival time of trigger signal and acoustic signal. Figure 2.4 depicts the timing of trigger and sound wave. The developed system is designed for 50 m distance range and the length of spread spectrum signal is 80 ms. Given this specification, the time interval between two successive signal was set as 250 ms.

Once the trigger signal is detected, then 240 ms data were saved and used to calculate correlation value (c) which can be calculated as,

$$c(t) = \sum_{n=0}^{N-1} s(n)\, r(n+t) \tag{2.2}$$

where t is time of received data, s is replica of transmitted signal and N is the length of s. Time of Flight (TOF) is then estimated by detecting the peak (maximum) of the calculated correlation value.

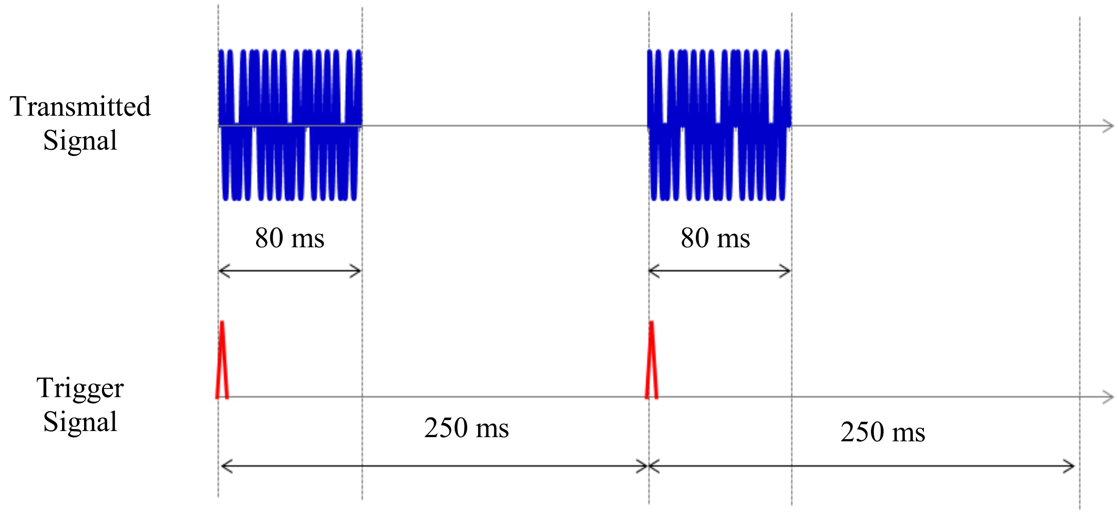

Figure 2.4. Timing of spread spectrum sound and trigger signal emission.

For fast computation, Fast Fourier Transform (FFT) was used. For Discrete Fourier Transform (DFT), cross-correlation $C_{xy}(k)$ of signal pair $x(n)$ and $y(n)$ can be calculated by taking Inverse Fast Fourier Transform (IFFT) of their cross-spectrum $\phi_{xy}(k)$ as follows,

$$\phi_{xy}(k) = \frac{1}{N} X^*(k)\ Y(k) \tag{2.3}$$

$$C_{xy}(k) = IFFT\ (\phi_{xy}(k)) \tag{2.4}$$

where $X^*(k)$ is complex conjugate of signal $x(n)$, $Y(k)$ is complex spectrum of signal $x(n)$, and N is the length of the signals. Based on this theorem, cross-correlation value of the received spread spectrum sound is calculated using the following steps,

a) Calculate FFT of the received signal $R(k)$
b) Calculate FFT of the replica signal $S(k)$
c) Calculate cross-spectrum of this signal pair as

$$\phi_{xy}(k) = S^*(k)\ R(k) \tag{2.5}$$

d) Take IFFT of the calculated cross-spectrum using Eq. (2.4).

Example of typical received, replica and correlation signals are shown in Fig. 2.5.

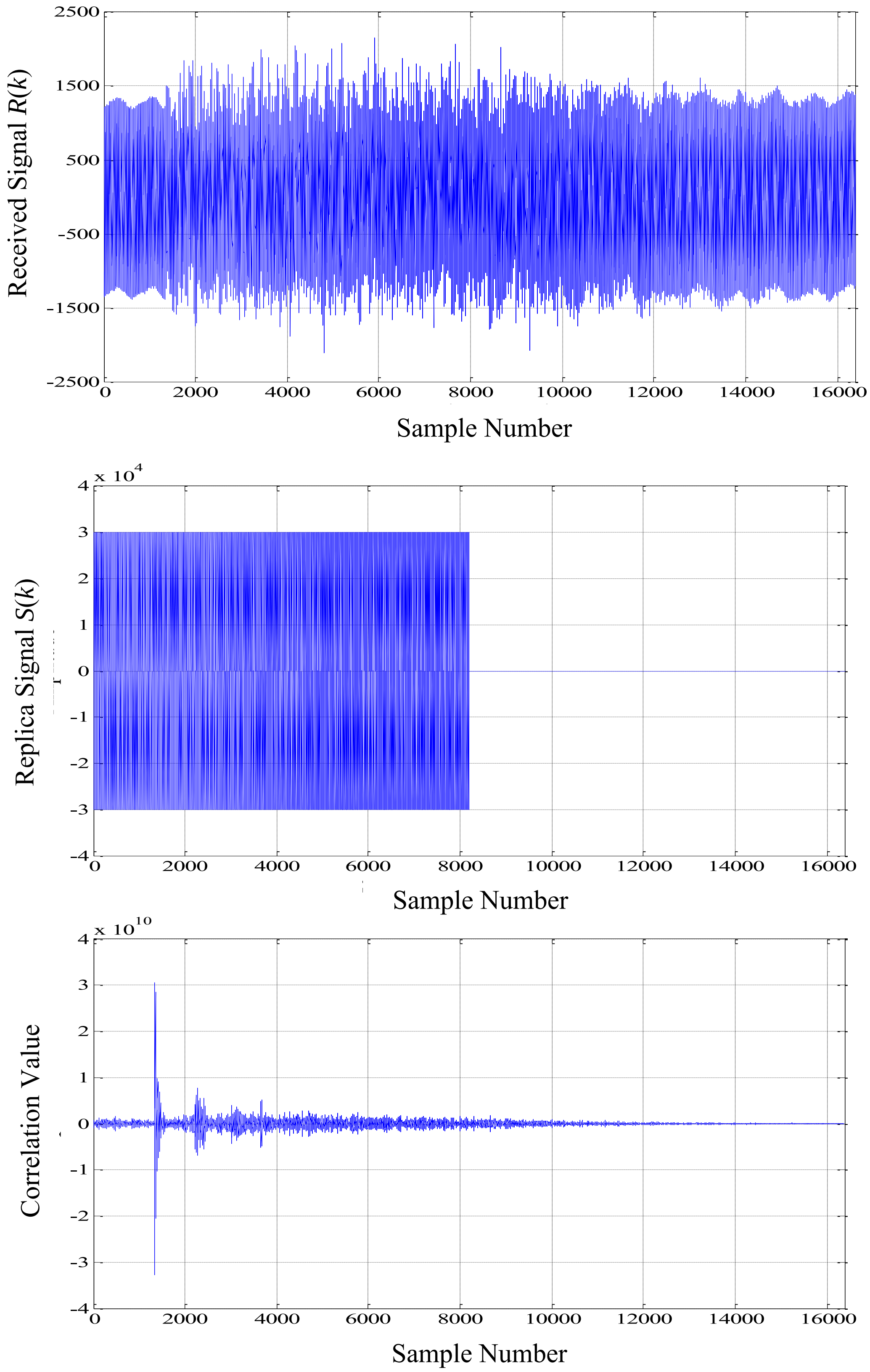

Figure 2.5. Example of a typical: (a) Received signal, (b) Replica of transmitted signal, and (c) Correlation value.

Using the estimated TOF, distance d from the transmitter to the receiver can be calculated as

$$d = v_s \ \Delta t \tag{2.6}$$

where Δt is time of flight of the sound wave and v_s is the speed of sound wave (in m/s). To get an accurate distance measurement, the influence of temperature T (°C) also needs to be taken into account. It can be done by using Newton-Laplace equation, which for practical use (e.g. as used in [19]) it can be approximated as:

$$v_s = 331.5 + 0.61\,T \tag{2.7}$$

2.2.3. Three-dimensional position estimation

To determine position of an object in three dimensional space (3D) using trilateration (Fig. 2.4.), it is required to get at least distance data from the object to three reference points set at known position. For sound based positioning system with GPS-like configuration (i.e. using multiple transmitters set at known position to localize a receiver), at least three transmitters are required. Position of the speaker then can be obtained by solving these equations. Here, an iterative least squares method was chosen as a solver.

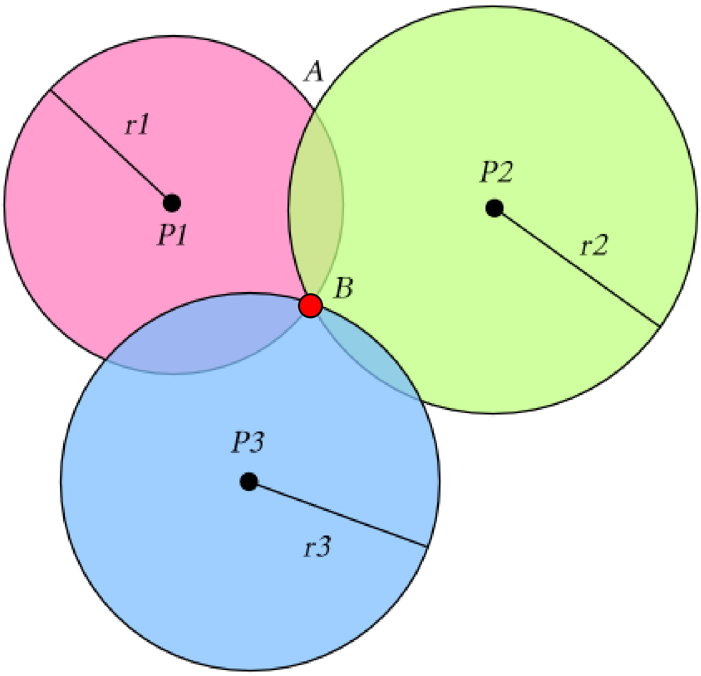

Figure 2.6. Position estimation using trilateration method. Using at least three distances (r_1-r_3) from known reference position (P_1-P_3) to estimate the position of unknown point (B).

Assuming the mobile station is located at an unknown position $M = (x_m, y_m, z_m)$ and the four reference nodes are located at known positions $N_i = (x_i, y_i, z_i)$ with i denoting number of each reference node. The distance from the mobile station to each node (d_{mi}) can be expressed as:

$$d_{mi} = \sqrt{(x_m - x_i)^2 + (y_m - y_i)^2 + (z_m - z_i)^2} \quad (2.8)$$

These data are obtained by using range measurement procedures as explained in previous section. First, estimated position is initialized as $P^0 = (x_m^0, y_m^0, z_m^0)$ and is used to calculate the estimated distance to each fixed node (d_{mi}^0),

$$d_{mi}^0 = \sqrt{(x_m - x_i)^2 + (y_m - y_i)^2 + (z_m - z_i)^2} \quad (2.9)$$

The difference of these distances (i.e. d_{mi} and d_{mi}^0) which is

$$\Delta d_{mi} = d_{mi} - d_{mi}^0 \quad (2.10)$$

then is used to determine partial difference (Δx, Δy, Δz) for correcting the value of x_m^0, y_m^0,and z_m^0 that can be calculated from the following equation,

$$\Delta d_{mi} = \frac{\partial d_{mi}}{\partial x}\Delta x + \frac{\partial d_{mi}}{\partial y}\Delta y + \frac{\partial d_{mi}}{\partial z}\Delta z \quad (2.11)$$

where

$$\frac{\partial d_{mi}}{\partial x} = -\frac{\left(x_m^0 - x_i\right)}{d_{mi}}$$

$$\frac{\partial d_{mi}}{\partial y} = -\frac{\left(y_m^0 - y_i\right)}{d_{mi}}$$

$$\frac{\partial d_{mi}}{\partial z} = -\frac{\left(z_m^0 - z_i\right)}{d_{mi}}$$

After obtaining Δx, Δy, and Δz, these values are then used to update the estimated position:

$$x_m^0 = x_m^0 + \Delta x \tag{2.12}$$

$$y_m^0 = y_m^0 + \Delta y \tag{2.13}$$

$$z_m^0 = z_m^0 + \Delta z \tag{2.14}$$

These procedures are then repeated until the partial difference values (Δx, Δy, Δz) converge into small value or until pre-determined iteration number has been achieved. Here, we used the second parameter as stopping criteria. The iteration is limited as 100 times.

2.3. Architecture of the Proposed Positioning System

2.3.1. System configuration

As shown in Fig. 2.7, basically there are two possible system configuration of sound-based positioning system namely GPS-like and inverse-GPS configuration. For GPS-like system, several transmitters are placed at known position and are used as reference nodes (N_i) to estimate the position of a receiver. In reverse, inverse-GPS system uses several receivers as references to estimate a transmitter.

Each configuration has its own advantage and disadvantage. As mentioned in [20], GPS-like system (or they refer as passive mobile architecture) scales better than inverse-GPS system (or active mobile architecture) as the number of devices increase. This is because the fact that for inverse-GPS system there is a need to send the received data to central database for further processing. When privacy is an important issue, although it may not be the case for agricultural applications, GPS-like system is also better than inverse-GPS system. However, for localization of a moving object, inverse-GPS system can provide much superior performance than GPS-like due to its capability to guarantee the simultaneity of the distance estimation.

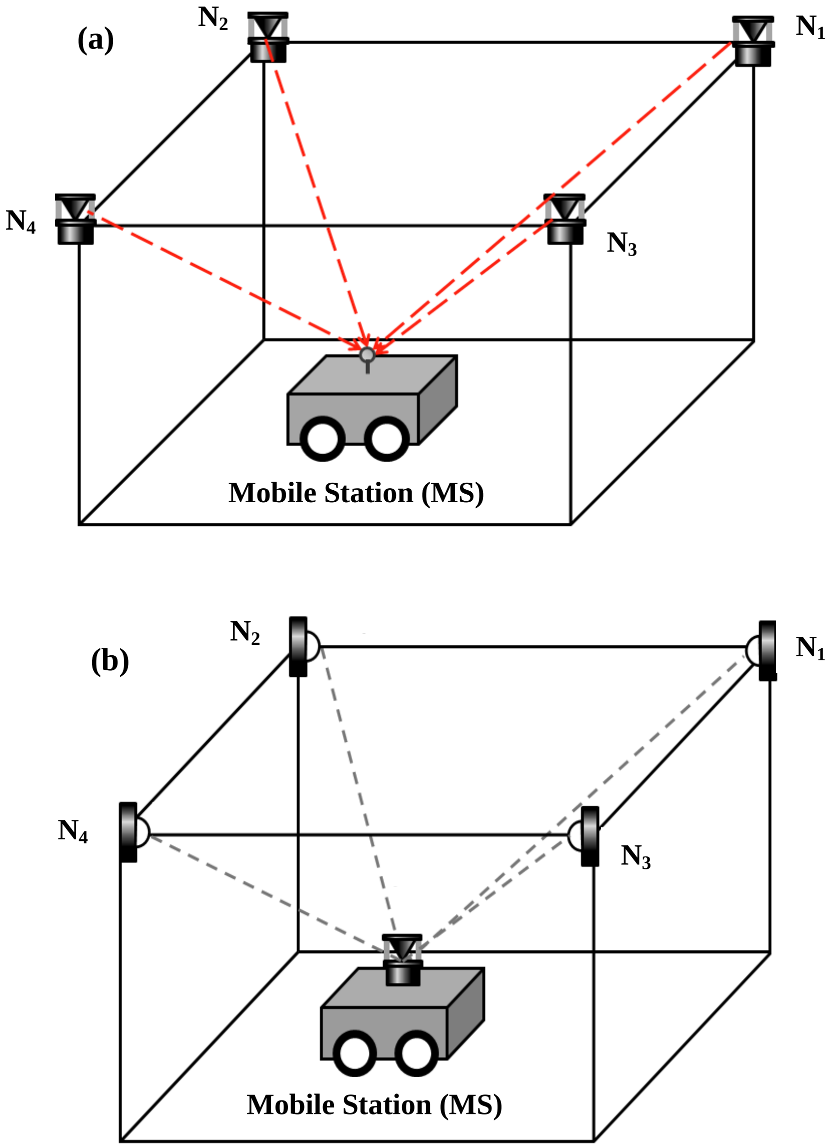

Figure 2.7. Basic setup of sound-based positioning system: (a) GPS-like setup and (b) Inverse-GPS setup.

2.3.2. Detail of the hardware

The hardware used in this work consisted of silicon microphones (MP0404UD, Knowles Electronics), a speaker (FT28D, Fostex Company), a sound interface (Octa-Capture, Roland Corporation), an amplifier (Kama Bay Amp Rev. B, Scythe Inc.), and a personal computer (Windows XP, Core 2 duo processor 2.66 GHz, and 3 GB RAM). For simplicity, a wired system was used here. In a real life application this would be replaced by a wireless system. Each microphone and mobile station is equipped with a digital thermometer to monitor surrounding temperature so that sound velocity could be adjusted for variation with temperature.

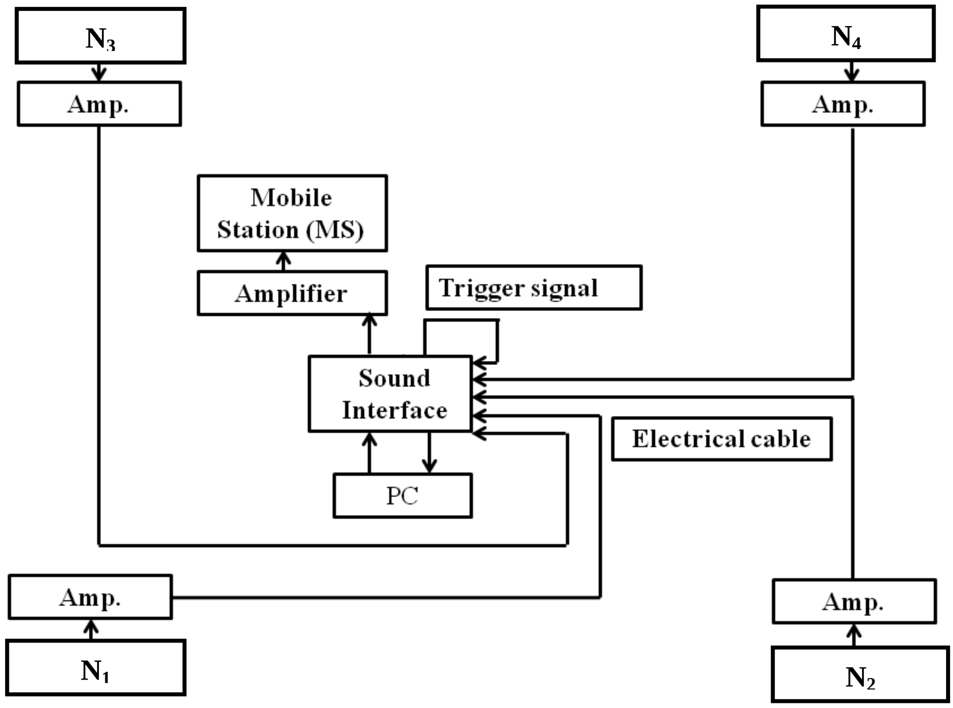

Figure 2.8. Schematic of wiring system of the proposed positioning system.

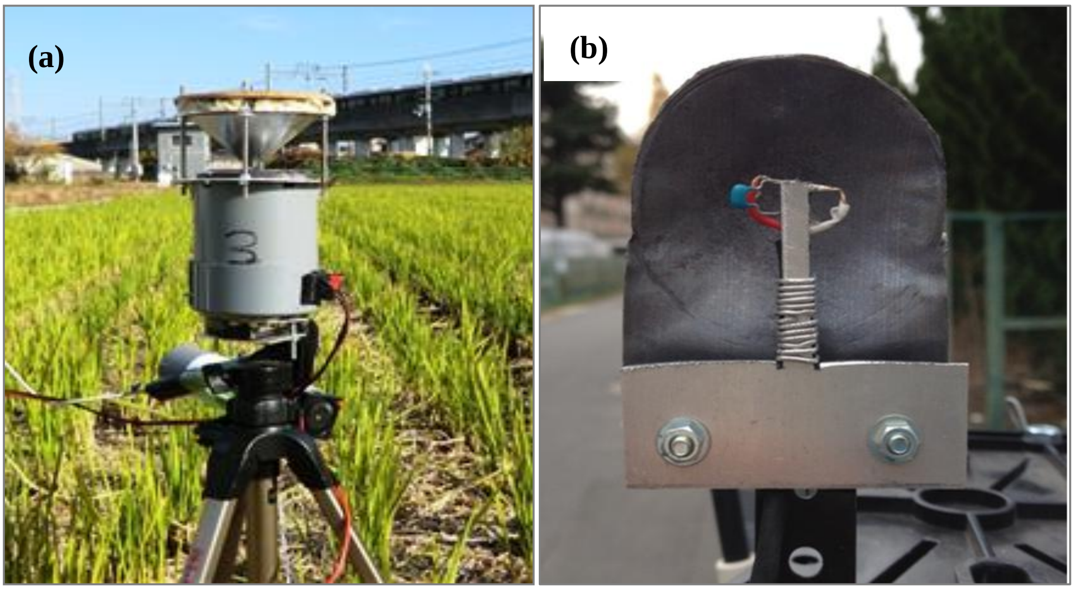

Figure 2.9. (a) Omni-directional speaker and (b) Microphone with parabolic cone are used as transmitter and receiver respectively.

Figure 2.10. Thermometer for monitoring surrounding temperature to adjust the sound speed.

2.4. Basic Performance Assessment

This section presents a basic performance assessment of the developed positioning system. As the basic of the whole system, the range measurement accuracy was investigated [21]. The experiment was conducted under the following condition: air temperature was 21.3 ~ 21.9 ^{o}C and wind velocity was less than 0.1 m/s, while sound pressure level was 35 dB. This condition is relatively ideal. There is no significant influence that may come from wind or temperature fluctuation.

Figure 2.11 and 2.12 show experimental results of distance measurement using the developed system with different sampling rate. The error bar indicates minimum-maximum error value. Theoretically the resolution of distance measurement using sampling rate 48 kHz and 96 kHz are 7.1 mm and 3.5 mm respectively. As expected, the results show that measurement with higher sampling rate will give better results as indicated by lower average error and also smaller deviation from minimum-maximum error value. The results confirmed that sampling rate has significant influence on measurement accuracy. Higher sampling rate will give higher accuracy. However higher sampling rate will lead to higher computation load and also requires hardware with higher computation capability.

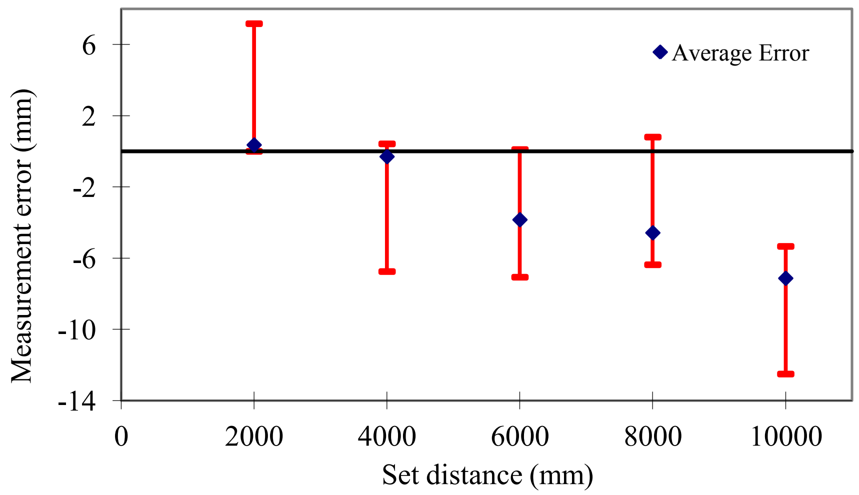

Figure 2.11. Distance measurement test using sampling rate 48 kHz [21].

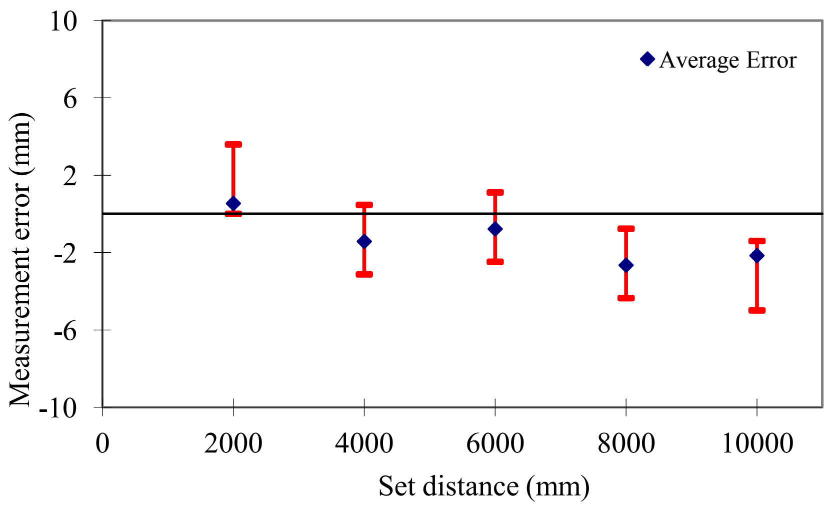

Figure 2.12. Distance measurement test using sampling rate 96 kHz [21].

2.5. Conclusion

This chapter discussed the basic of spread spectrum sound-based positioning system that has been developed and was used for entire work presented in this thesis. It covers, in brief, all aspect of the developed system including generation of spread spectrum sound, detail hardware, as well as formulation that underlying range measurement and position estimation.

Some basic assessment through experiments was also presented and it confirmed the successful development of the proposed system. All experiments were conducted in laboratory which is relatively in controlled condition Experimental results showed that for range measurement of 10 m distance in relatively quiet condition and no influence of wind, the proposed system could achieve a few millimeters accuracy. The results show that it strongly depends on the sampling rate. The obtained results have demonstrated the promising potential of spread spectrum sound-based positioning system. It is, however, still in very early stage of the development of sound-based positioning system to be applied in agricultural area. In the actual application, there are many influencing factor that may interfere and degrade the performance. This is the main issue that tries to be addressed in the next following chapters.

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Chapter 3

*Wind Compensation Method for Spread Spectrum Sound-based Positioning System by Using a Base Station**

Summary

In recent years, development of sound-based positioning system especially for indoor environment has attracted great attention of many researchers. Sound-based positioning system owns some merits compared to other systems that are cheap and also can provide high positioning accuracy. This system, especially using ultrasound, has been widely used in some robotics applications especially for navigation of mobile robot. This system is also well known in area of ubiquitous or pervasive computing. Many location-aware applications have been developed using such kind of system.

Although this system has been well developed in many areas, there is only limited report about its use in the agriculture field. The main reason for this limitation is related to the nature and characteristic of the agricultural field that has a high vagueness and uncertainty of the environment. There are special characteristics of agricultural environment which are much different from those where previously developed system were applied (e.g. laboratory, office, manufacturing building). The main challenges are related to temperature gradients, wind, humidity, background noises and the presence of obstacles. These factors influence the sound wave and will also influence the positioning accuracy. Therefore developing a sound-based positioning system in agricultural area is still a challenging task.

In this paper we propose a wind compensation method using base station for spread spectrum sound-based positioning system. A similar approach was also introduced in some previous related works. The main point which makes this work differs from their work is that we try to take the advantage of the use of spread spectrum sound, instead of ultrasound, for position

**Full version of this chapter has been submitted for publication*

estimation in wider area and with different environment condition (i.e. for agricultural setting). Because there are two sources of sound wave were used, a multiple access technique was required. In this case, the use of two different multiple access techniques, Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) was investigated to determine the most appropriate one for this application. We also investigated the influence of the base station location to find out the best setup which gives better performance

The basic idea of the proposed wind compensation method is to use known sound velocity vectors obtained from a Base Station (BS) set at known position to estimate profile of sound velocity vectors at a Mobile Station (MS) to be located. In this work, we consider to use such kind of compensation method for simple distance measurement (1D) and for position estimation (2D) cases. For simplicity reason, we do not consider 3D case and also considering the designated working area (proportion of length, width, and height), we consider that the sound velocity vectors estimated in 2D are also applicable in 3D case without significantly decrease the performance.

To evaluate the effectiveness of the proposed system, two experiments were conducted at Kyoto University and Kyoto University experimental farm, Takatsuki, Osaka, Japan. The first experiment was conducted to select the proper multiple access technique. Here, the performance of Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) was investigated. The second experiment was to investigate the influence of location of the BS in order to determine the optimal setup as well as to evaluate the effectiveness of the proposed wind compensation for improving positioning accuracy.

From the first experimental results, it can be concluded that the proposed wind compensation method could improve measurement accuracy using both TDMA and CDMA techniques. In most cases, the distance measurement error could be minimized. Other thing that also could be observed from these results is that TDMA outperforms CDMA, especially in term of robustness and the maximum range that can be reached. CDMA technique could give good measurement accuracy within 20 m distance only, and it is suffering from misdetection problem for longer distance. However, it was not observed for TDMA. It indicated that CDMA is less robust than TDMA.

The main problem related CDMA technique is due to the near-far problem. This problem occurred when two spread spectrum sounds are transmitted simultaneously from two speakers which are located in different distance from one microphone. The power of sound from nearer speaker is much higher than farther speaker. Therefore it makes difficult to detect the incoming sound from the farther speaker.

The error observed was not solely from the influence of the wind. It also may also come from error of sound velocity estimation at BS. It is considered as property or limitation of the proposed method. As discussed in previous chapter, the accuracy of distance measurement depends on the sampling frequency which is used for acquiring data. In this case, for 96 kHz sampling frequency, the accuracy is about 3.5 mm.

In the second experiment, we observed performance of the wind compensation method using two BS setups, inside and outside of the working area. For the first setup where the BS was set at the center of the working area, for all cases the proposed wind compensation performed very well. In average the positioning error was reduced from 69.7 mm to 20.2 mm. Different results observed in the second setup where the BS was set outside of the working area. In average, positioning accuracy with and without compensation was just slightly better or about the same. They were 86.9 mm and 88.7 mm, respectively.

This result suggested that some assumptions used in the proposed compensation method need to be re-evaluated. Result from the first setup proved the assumption that sound velocity changes linearly and therefore the sound velocity for certain direction can be estimated using interpolation of other two known values. However, further investigation is needed to find out the actual range in which this assumption/approach is still applicable. For the second setup, because the estimated sound velocity at the BS only covers direction of half of the working area, sound velocity vector for another half area should be estimated from inverse-sound velocity. From the experimental result, it can be concluded that the sound behavior did not follow the assumption underlying this formulation and hence this approach could not be used. We also observed that the closer the measuring point to the BS, the better the accuracy could be achieved and vise versa.

These results suggested that the best position for BS is at the center of the working area. However, when it is used, for example, for navigation of mobile robot, it will limit mobility of the robot. Another option is by using two BS at two sides of the working area to make sure that sample of the sound velocity vectors can cover all area. However if these two BS transmit sound simultaneously, in case of using CDMA it will be suffering from near-far problem and if other technique that is Frequency Division Multiple Access (FDMA) used, there is a need to negotiate the assignment of frequency bands. In the other hand, if the sound is not transmitted simultaneously (i.e. using TDMA), it will make updating time become longer. Thus, using one BS is likely more preferable.

Beside those limitations, there is also another critical issue about TDMA when this technique is applied for developing positioning system, which is related to the updating time. As comparison, with current system, position of MS can be updated every 250 ms by using CDMA and 500 ms by using TDMA respectively. However, considering near-far problem in CDMA system, the result suggested that TDMA is better and more reliable to be used for developing sound-based positioning system with wind compensation.

The low updating rate (2Hz) is in-sufficient for some applications that required higher update rate e.g. navigation system of autonomous vehicle. For general application, updating rate of 10 Hz is enough. Alternative solution for this issue is by combining this system with other positioning method e.g. dead reckoning method using odometry and Inertial Measurement Unit (IMU). In this case fusion technique such as Kalman filter can be used. This approach is also widely adopted for GPS-based navigation system. Regarding to the mobility issue, actually it still can be resolved because position of the BS is fixed and has been known.

For further improvement, especially related to updating time which is critical for some applications, near-far problem in CDMA must be solved. In this case, the use of interference canceller that is well known in area of communication system can be considered as one of the possible solutions.

Chapter 4

Moving Object Localization Using Sound-Based Positioning System with Doppler Shift Compensation

Abstract

Sound-based positioning systems are a potential alternative low-cost navigation system. Recently, we developed such an audible sound-based positioning system, based on a spread spectrum approach. It was shown to accurately localize a stationary object. Here, we extend this localization to a moving object by compensating for the Doppler shift associated with the object movement. Numerical simulations and experiments indicate that by compensating for the Doppler shift, the system can accurately determine the position of an object moving along a non-linear path. When the object moved in a circular path with an angular velocity of 0 to 1.3 rad/s, it could be localized to within 25 mm of the actual position. Experiments also showed the proposed system has a high noise tolerance of up to -25 dB SNR without compromising accuracy. It also confirmed that it worked well under the influence of wind.

4.1. Introduction

Automated robotic systems in agriculture have been studied extensively in the last few decades [1, 2]. It has been applied to various agricultural operations, such as weeding [3, 4], plant monitoring [5], application of fertilizer and chemicals [6], and harvesting [7-9]. However, to date there have been limited commercial applications of these agricultural robots; mainly due to their high cost. Among the components that make up an automated agricultural robot, the navigation system is a major contributor to the total development cost. A reduction in the price of the navigation system, combined with optimum operating time, will enable autonomous agricultural vehicles to become economically feasible [10]. Thus, the

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development of a low cost navigation system is critical to realizing the wide spread use of commercial agricultural robots.

In existing agricultural vehicle navigation systems (see [11] for a brief review), a Real Time Kinematics Global Positioning System (RTK-GPS) is the most widely used for determining vehicle position. It can provide very high positioning accuracy. However, due to the high price of RTK-GPS, it is also considered to be the main component contributing to the increased cost of these robotic systems [12]. Therefore, finding an alternative low cost positioning system is highly sought after. The use of a sound-based local positioning system has the potential to achieve this. Compared to other alternative positioning systems, it offers a number of merits. It can provide high positioning accuracy at a relatively low cost. There have been many reports of the development of sound-based positioning systems in an indoor environment, such as Active Bat [13], Cricket [14, 15], Dolphin [16-18], and 3D-Locus [18, 19]. However, only a limited number have documented the use of such a system in an outdoor environment.

In the current research, we develop an alternative outdoor navigation system for agricultural autonomous vehicles using a sound-based positioning system. Although ultrasound has been widely used in previous research, we use a spread spectrum sound. There are a number of characteristics that recommend such an approach for this application. It has high noise tolerance, as well as high signal identification properties [20]. Also, as mentioned in [21], high measurement accuracy can be achieved using this kind of system due to the large bandwidth and continuous nature of the spread spectrum approach.

To date, this approach has been applied to non-agricultural settings [18-19, 22-25]. In the current research, we optimize the system to an agricultural setting, where conditions are substantially different from previous applications. For instance, in order to obtain high positioning accuracy there are many factors that need to be taken into account, such as temperature gradient, wind, background noise, and the presence of obstacles. We used spread spectrum sound in which part of its spectrum is in the range of audible sound. Hence, it gives an advantage of the low frequency sound waves for handling the obstacles issue [22, 26]. Although it will generate additional noise, it is considered to be more applicable to an agricultural setting where many obstacles are present.

In previous work [27], we found that high positioning accuracy can be achieved using this positioning system for a stationary object. Within a 30 m x 30 m outdoor area, in average, the position of a stationary object was estimated with accuracy around 20 mm. This accuracy level is sufficient for many applications, including navigation of autonomous agricultural vehicles. The next step is to develop a system, for localization of a dynamic/moving object. Such a sequential development process has been used effectively to develop other systems [21, 28].

To accurately locate an object, it is first necessary to accurately measure distances to that object. In the proposed sound-based positioning system, distance is calculated by measuring time of flight (TOF) of the sound wave to or from the object and then multiplying by sound velocity. When an object is in motion, there is a frequency shift of the transmitted sound wave due to the Doppler Effect. Thus, the correlation calculation between received signal and replica signal will be affected, resulting in an inaccurate estimation of the TOF and therefore distance estimation. This will in turn mean a decreased accuracy in localization. Even more, for faster moving objects, a system without Doppler compensation cannot be expected to accurately localize the object.

There are alternative solutions for moving object localization by using sound wave proposed in previous works. Among of them, filtering method such as Kalman filter [21] and particle filter [28- 29] are the most popular. In [25], tracking method with limited range of correlation calculation was proposed for moving object localization using spread spectrum ultrasonic wave. In their work, they used limited correlation range instead of full range to prevent decreasing of correlation value. As stated, using this approach a moving object with speed of 0.2 m/s could be realized within an average error of 50 mm. Another approach was proposed in [30]. They develop a Doppler-tolerant receiver for ultrasonic positioning system by using Kasami sequence. Simulation results showed the capability of the system to detect the signal emitted by moving device with velocity up to 3 m/s. The real experiment results unfortunately did not show the actual best performance that can be achieved due to manufacturing defect and problem for performance evaluation when the robot is turning.

In this paper, we propose an alternative approach for accurate localization of moving objects by compensating for the Doppler shift associated with the movement. This approach is similar to that used in [31, 32]. Beside the methodology for compensating for the Doppler shift associated with moving objects, we also present performance evaluation results using this proposed localization system. Furthermore, we also investigated the potential of noise to interfere with the performance of the proposed system.

4.2. Spread Spectrum Sound-based Positioning System

4.2.1. System configuration

Figure 4.1 shows the configuration of the spread spectrum sound-based positioning system used. The proposed system applies an inverse-GPS configuration, where four microphones are installed at known positions as fixed nodes and one omni-directional speaker is installed on a mobile platform (mobile station). Photos of the microphones and omni-directional speaker used in this work are shown in Fig. 4.2.

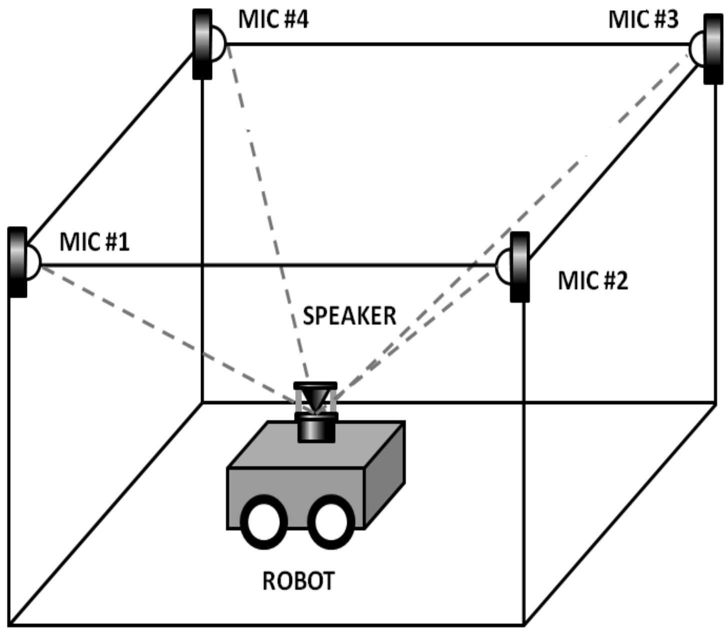


Figure 4.1. Configuration of spread spectrum sound-based local positioning system.

This equipment consisted of silicon microphones (MP0404UD, Knowles Electronics), a speaker (FT28D, Fostex Company), a sound interface (Octa-Capture, Roland Corporation), an amplifier (Kama Bay Amp Rev. B, Scythe Inc.), and a personal computer (Windows XP, Core 2 duo processor 2.66 GHz, and 3 GB RAM). For simplicity, a wired system was used here. In a real life application this would be replaced by a wireless system. Each microphone and mobile station is equipped with a digital thermometer to monitor surrounding temperature so that sound velocity could be adjusted for variation with temperature.

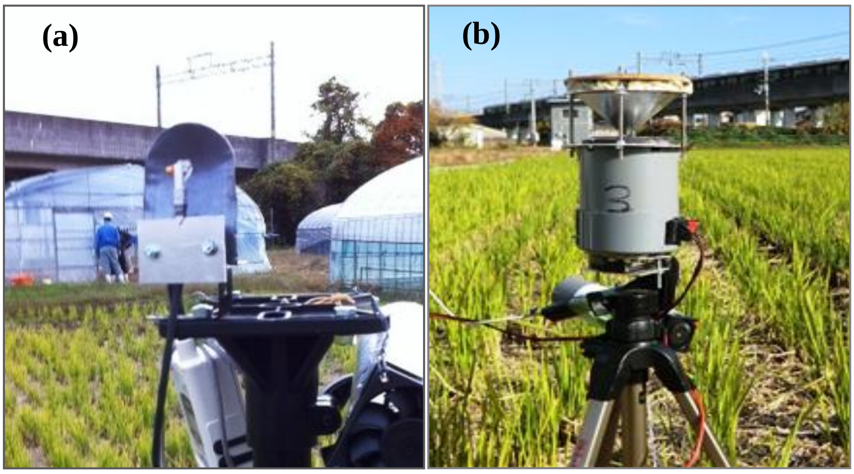


Figure 4.2. (a) Microphone. (b) Omni-directional speaker.

The spread spectrum sound was created from a maximum length sequence (M-sequence), pseudo random code with Binary Phase Shift Keying (BPSK) modulation [33]. The main parameters of the emitted signal were the carrier frequency, the length of the sequence, and the number of carrier cycles per code chip (chip rate). For signal detection the sampling frequency and sampling bit, as well as other parameters were set as shown in Table 4.1. To synchronize signal reception for all microphones, especially for arrival time calculation, a trigger signal is also sent at the time of spread spectrum sound emitted from the speaker.

Table 4.1. Property of spread spectrum sound

Property	Value/Remark
Sampling frequency (f_s)	96 kHz
Sampling bit	16
M-sequence length	1023
Modulation	BPSK
Carrier wave frequency (f_c)	24 kHz

4.2.2. Position estimation method

To estimate the position of an object in three-dimensional space, it is necessary to have at least three distances from that object to known fixed nodes. Because our system used an inverse GPS configuration, position estimation was as follows: when the speaker on the mobile station is located at an unknown position $M = (x_m, y_m, z_m)$ and the four nodes are located at known positions $R_i = (x_i, y_i, z_i)$ with i denoting each of the four nodes. Using the estimated distance from the speaker to each node (d_{mi})

$$d_{mi} = \sqrt{(x_m - x_i)^2 + (y_m - y_i)^2 + (z_m - z_i)^2} \tag{4.1}$$

$$d_{mi} = v_s \ \Delta t_{mi} \tag{4.2}$$

where v_s is sound velocity and Δt_{mi} is Time of Flight (TOF) of the sound wave, the position of the speaker can be obtained by solving these equations. Here, a least squares method was used to solve the equation. To calculate TOF, the trigger and arrival time of the signal were first estimated using cross-correlation. Then, TOF was calculated as the difference between these two times. Thus, determining detection time, obtained by detecting the peak correlation value, was critical, as this determines the accuracy of the distance measurement, as well as positioning accuracy. This will be elaborated on below.

4.3. Doppler Shift Compensation

Signal arrival time was obtained by calculating a cross-correlation value C_i from the received signal $r_i(n)$ and a replica of the transmitted signal $s(n)$ using Fourier transform:

$$C_i = \sum_{n=0}^{N-1} s(n)\, r_i(n+t) \tag{4.3}$$

where n = 0, 1, 2 … N-1 with N is the number of samples used in the Fourier transform calculation. For efficient calculation, a Fast Fourier Transform (FFT) was used to calculate the correlation value as follows:

$$C_i = IFFT\left(conj.\left(S(n)\right) R_i(n)\right) \tag{4.4}$$

where $conj.(S(n))$ and $R(n)$ are the complex conjugate of FFT of $s(n)$, and the complex spectrum of FFT for $r_i(n)$, respectively. IFFT denotes the Inverse Fast Fourier Transform.

After calculating cross-correlation, threshold operation was applied to get peak values. The arrival time is then estimated from the first detected peak. The threshold value C_{th} is set as:

$$C_{th} = \frac{C_{\max} + C_{ave} + 3\,\sigma_{corr}}{2} \tag{4.5}$$

where C_{max}, C_{ave}, and σ_{corr} are maximum value, average, and standard deviation of cross-correlation. Based on the three-sigma rule, for normally distributed data, 99.7% data can be represented by $C_{ave} + 3\ \sigma_{corr}$. However, there is no information about the data distribution of correlation signal. Therefore C_{max} value was added. We used half of this value as the threshold and it works well for our system.

To compensate for the Doppler shift, another sound wave is added to the spread spectrum sound. Thus the transmitted sound wave $s(n)$ is changed from (4.6) into (4.7)

$$s\,(n) = \sin\left(\frac{2\pi\, f_c n}{f_s}\right) \times M(m) \tag{4.6}$$

$$s\,(n) = \sin\left(\frac{2\pi\, f_c n}{f_s}\right) \times M(m) + \sin\left(\frac{2\pi\, f_{ds} n}{f_s}\right) \tag{4.7}$$

with:

$$m = round\left(\frac{f_c}{2\,f_s}\,n\right) \tag{4.8}$$

where f_c = frequency of carrier wave, f_s = sampling frequency, f_{ds} = frequency of sound wave used for detecting Doppler shift. Here, f_{ds} is set to 36 kHz.

The Doppler shift is then estimated by detecting the maximum value of the power spectrum (f_{ds_max}) in the range 35.84 – 36.16 kHz. This range can be used to detect a frequency shift caused by an object moving at a speed of up to 1.5 m/s. This speed is thought to be commensurate with general agricultural operations. FFT was calculated from 16384 samples for FFT calculation, giving 5.86 Hz frequency resolution for Doppler shift estimation. The Doppler shift can be calculated as follows:

$$\Delta f_{ds} = f_{ds\_\max} - f_{ds} \tag{4.9}$$

Using this information, a new replica of the transmitted signal is re-generated using (4.7), replacing f_c with the new value (f_{c_new}) as follows:

$$f_{c\_new} = f_c + \left(\frac{f_c}{f_{ds}} \right) \Delta f_{ds} \qquad (4.10)$$

A cross-correlation is then calculated using this new replica signal and the detected signal using (4). A summary of the proposed Doppler shift compensation is depicted in Fig. 4.3.

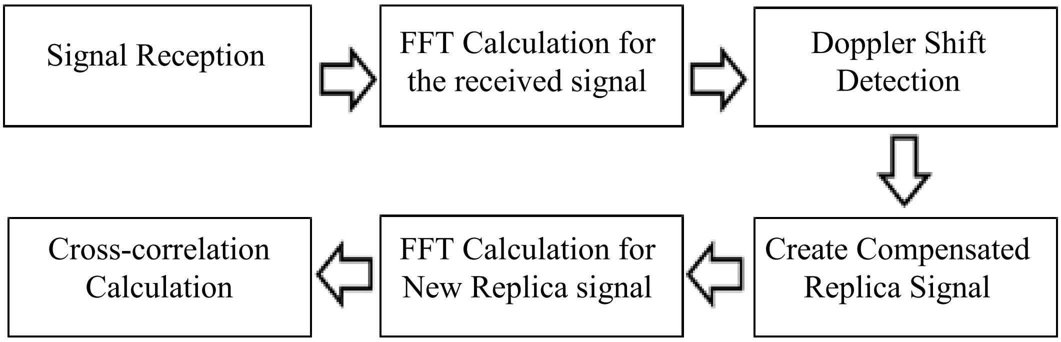


Figure 4.3. Schematic of the proposed Doppler-shift compensation method.

4.4. Experimental Setup

To evaluate the performance of the proposed method, we conducted several experiments to localize a moving object in one dimension (1D) and two dimensions (2D). Because the developed positioning system is aimed to be used in agricultural area, it is also important to investigate the performance of the proposed compensation method under the influence of wind and noises. Hence, some experiments were also conducted for this purpose.

4.4.1. The influence of moving speed

In the first experiment (Fig. 4.4), the influence of moving speed on the performance of the proposed method was examined. An omni-directional speaker was placed on a conveyor as the object to be localized. The conveyor could move at variable speeds in both directions: toward and away from the microphone. In this experiment, the distance to the moving speaker (with respect to the microphone) was measured periodically using the spread spectrum sound system, with and without Doppler shift compensation.

As the measure to evaluate, the localization performance in terms of position error, as well as signal identification, as indicated by signal to noise ratio of cross-correlation (correlation

SNR or SNR_{Corr}) were compared. First, the incoming signal (C_{sig*}) was detected for the case of with Doppler shift compensation and correlation SNR was calculated as:

$$Noise^{*} = \frac{\left(\sum_{i=0}^{N-1} C_i^{*}\right) - C_{sig}^{*}}{N-1} \quad \text{; for } C_i > 0 \tag{4.11}$$

$$SNR_{Corr}^{*} = \frac{C_{sig}^{*}}{Noise^{*}} \tag{4.12}$$

Asterisk symbol (*) denotes system with Doppler shift compensation. Using the same sample number as C_{sig}^{*} (the *i*-th sample where $C_i^{*} = C_{sig}^{*}$) then the same procedure was used to calculate correlation SNR of the non-compensated system. The experiments were conducted indoors to prevent other undesirable influences, such as wind and noise from interfering. We also compared the result with theoretical values obtained from numerical simulations.

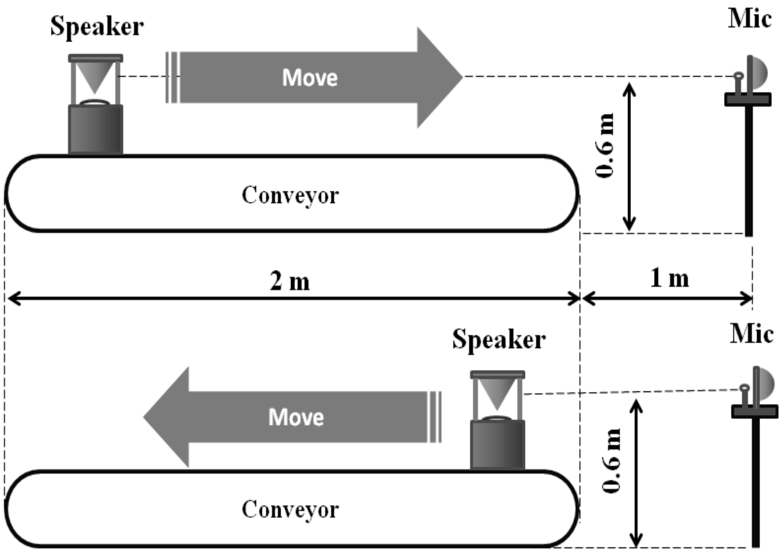


Figure 4.4. Experimental setup for the moving object localization in one dimension (1D).

4.4.2. Moving object localization test

To evaluate the performance of the proposed method to localize an object moving along a non-linear path, we developed a test bed as illustrated in Fig. 4.5. An omni-directional speaker was mounted on a mobile platform that could move in a circular path with an angular velocity (ω) between 0 – 1.3 rad/s. Stepping motor (Plexmotion SSA-PR-42D4, Shinano Kenshi Co., Ltd., Japan) was used to generate the motion and the desired angular velocity was achieved by controlling input signal sent to the motor. As the floor was relatively flat, only positioning in 2D space was considered in this evaluation. Trials at different angular velocities were performed to evaluate the influence of object speed on localization performance.

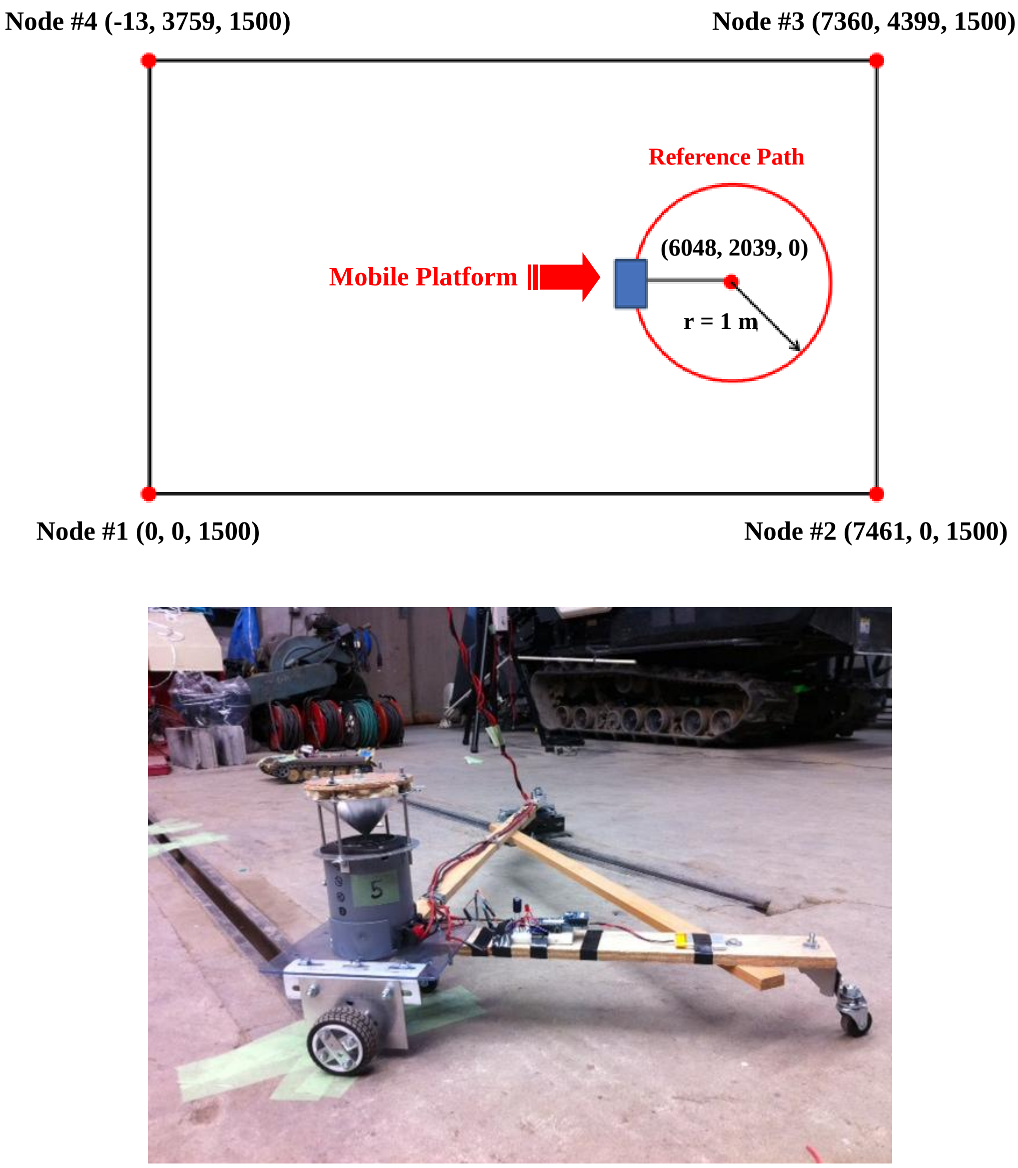


Figure 4.5. A testbed for moving object localization using spread spectrum sound.

4.4.3. The influence of wind

As discussed in the previous chapter that wind is one of the most influencing factors especially for outdoor application. Hence, we also investigated the performance of the proposed Doppler shift compensation under the influence of wind. For this experiment, the setup was the same with previous one. Wind influence was generated by adding electric fan

(Fig. 4.6). There are three level of wind speed can be generated from this fan namely low, medium, and high which equal to 1.5 m/s, 3.4 m/s, and 5.6 m/s respectively (all values are measured at 1 m distance in front of the fan).

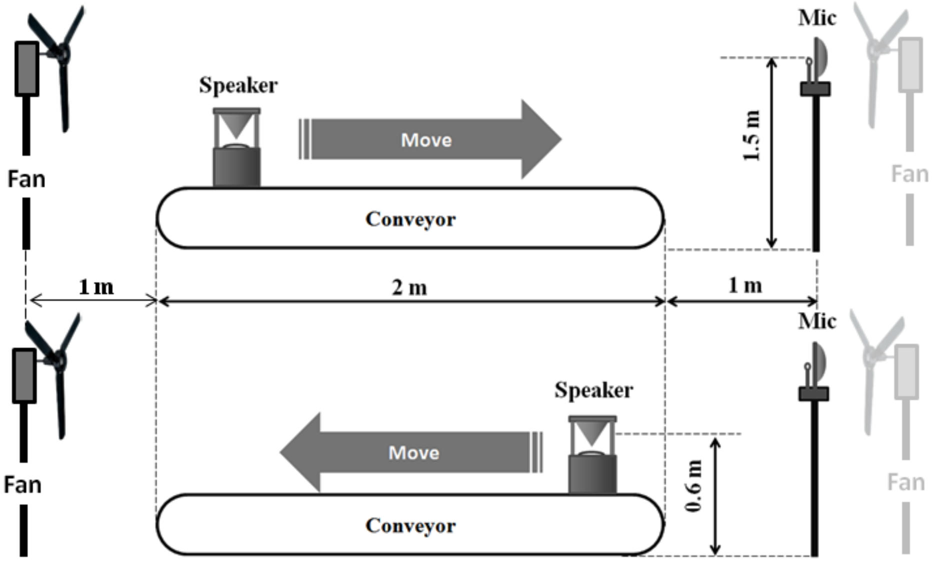


Figure 4.6. Experimental setup for evaluating the influence of wind.

4.4.4. The influence of noise

Background noise is common in an agricultural setting, especially in open fields. Therefore we also investigated the influence of background noise. Using the same setup as in Fig.4.4, white noise sound with different sound signal to noise ratio (sound SNR) was introduced to simulate background noise. Sound SNR is calculated as:

$$Sound\ SNR = 20\log_{10}\left(\frac{sound}{noise}\right) \tag{4.13}$$

Seven noise levels were trialed: 0, -5, -10, -15, -20, -25, and -30 (all values in dB). The performance was then evaluated by using correlation SNR as described in (4.11) and (4.12).

4.5. Results and Discussion

In this section both simulation and experimental results are presented. The simulation results were conducted to give an extended perspective on the experiment results obtained.

4.5.1. The influence of moving speed

Figure 4.7 and 4.8 shows a profile of the distance to the moving speaker with respect to the microphone in a 1D case. From a start position, the speaker moves at a set speed for a few seconds and then stops. While stationary, the distance to the object was accurately determined. However, when the object is moving, the localization estimates obtained without compensating for the Doppler shift, were quite inaccurate. When the Doppler shift was compensated for, there was accurate localization of the object. Due to limitations of the conveyor's controller, only two speeds were used in this experiment: 0.2 m/s and 0.8 m/s.

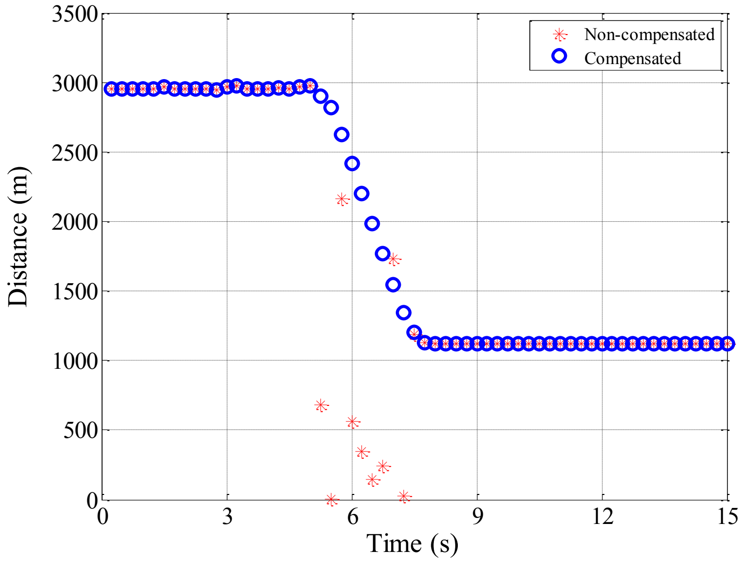


Figure 4.7. Profile of distance travelled by a speaker moving toward microphone.

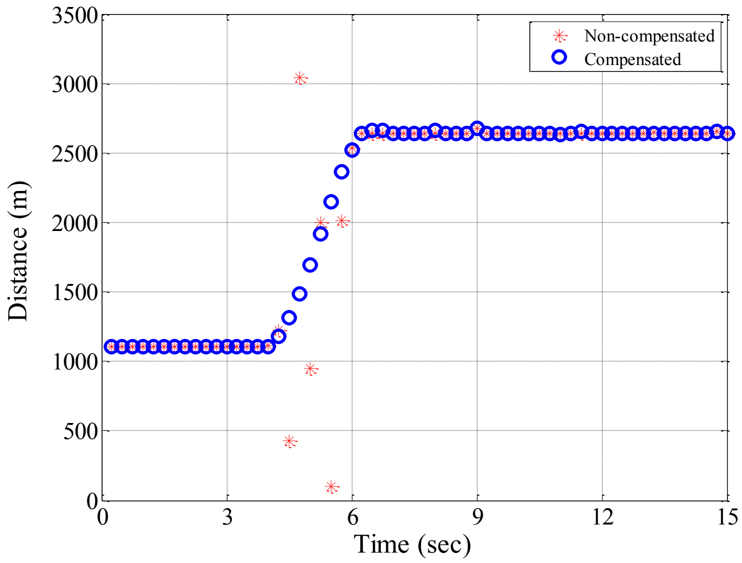


Figure 4.8. Profile of distance travelled by a speaker moving away from microphone.

To further analyze the influence of object speed, numerical simulations in Matlab were conducted. As shown in Fig. 4.9, the correlation value of the detected signal obtained from the numerical simulation was in good agreement with the experimental results. This indicates simulations can be used to extend the analysis as well as the understanding of the influence of object speed on the proposed localization method.

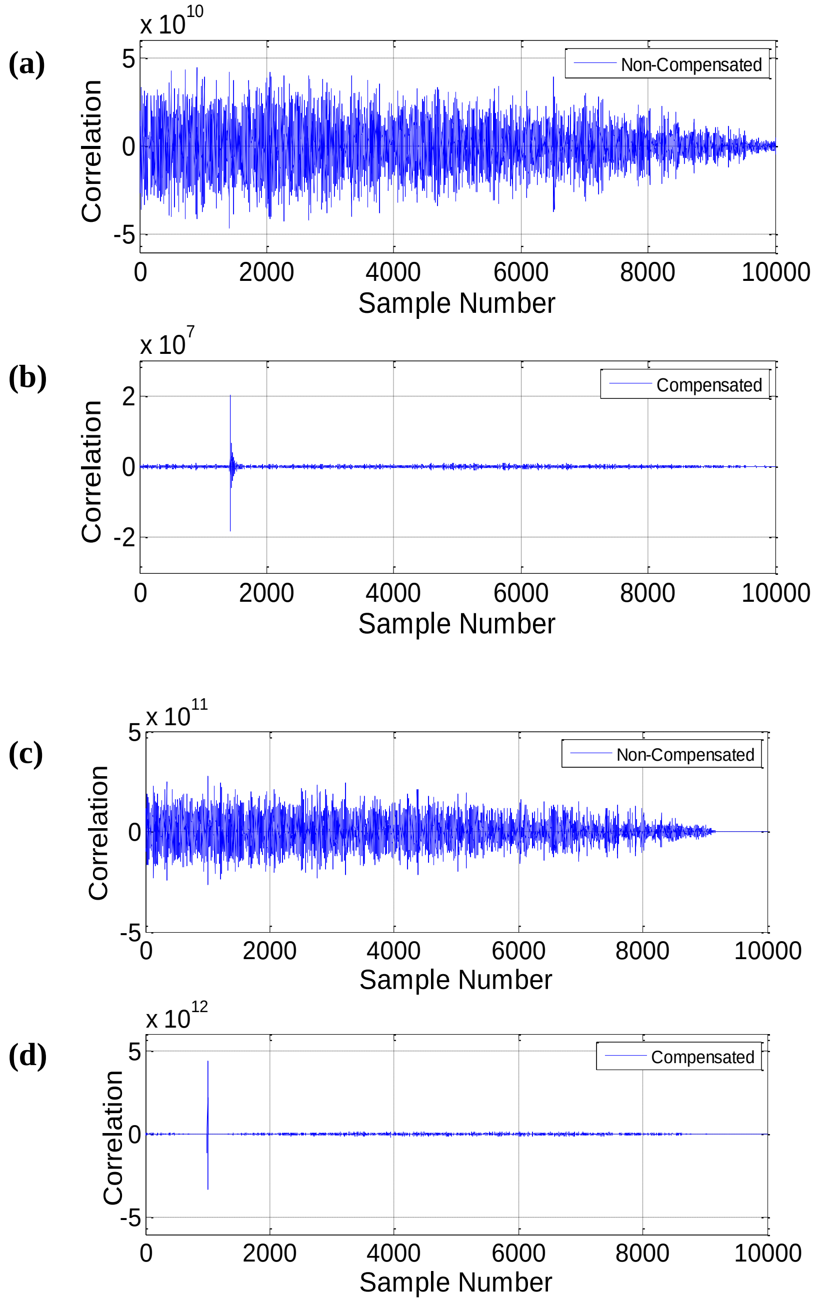


Figure 4.9. Correlation value at speed 0.2 m/s: (a) Without Doppler shift compensation and (b) With Doppler shift compensation obtained from experiment; (c) Without Doppler shift compensation and (d) With Doppler shift compensation obtained from simulation

The correlation SNR, as described in (4.11) and (4.12), is used to compare localization performance with and without Doppler shift compensation. This value indicates the ease with which peak correlation could be detected, which is critical for distance measurements using sound waves. The higher the correlation SNR value, the easier the incoming signal could be detected. As shown in Fig. 4.10, when attempting to localize without compensation, the correlation SNR values decreased with increasing object speed. For localization with Doppler shift compensation, there was no significant influence of object speed. This result concurs with the experimental results shown in Fig. 4.7 and Fig. 4.8. When the object (speaker) was moving at 0.8 m/s the correlation SNR was almost zero. Thus, it was difficult to detect the incoming signal correctly and as a result it failed to provide a correct position for the object when there was no Doppler shift compensation.

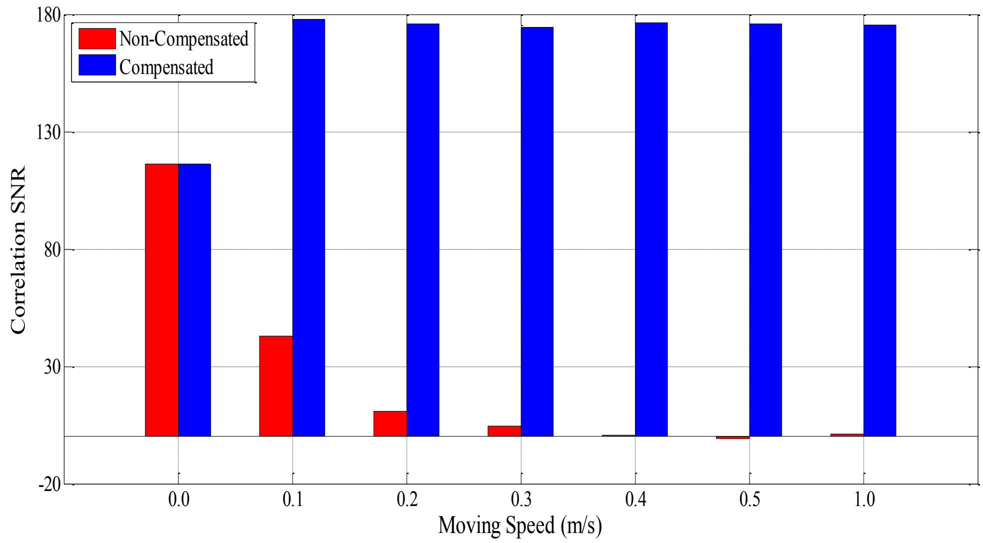


Figure 4.10. Comparison of correlation SNR for different moving speed with and without Doppler shift compensation.

In general the proposed method can significantly improve the localization performance. However in a few cases, an error is still observed. As shown in Fig 4.11, although it is not usual case, an error was observed for distance measurement using compensated method but not for non-compensated. After checking the correlation value for each method, we found there was a problem on Doppler shift detection. As shown in Fig 4.12a, for non-compensated method, even though little bit noisy, there was only single correlation peak that clearly observed and hence can be easily detected. It gave good distance estimation. In the other hand, for the compensated method, it seems to be less noisy however there were several peaks observed. Further the maximum value was likely not the true peak that leads misdetection and inaccurate distance estimation.

This result is mainly due to misdetection of the Doppler shift. In the current system, Doppler shift is only observed from the peak of power spectrum of additional sound wave at around 36 kHz. As shown in Fig 4.12d, there were two peaks observed, one with frequency >36 kHz and the other with frequency <36 kHz. In this case, it is likely the system select the wrong value to recreate replica signal and yield inaccurate estimation. Furthermore, two peaks detected in this experiment indicated that there was a direction change of object movement. Firstly the speaker may move toward the microphone then it changes to move away from microphone and vise versa. It indicated that there was vibration occurred. It may happened especially during acceleration or deceleration stage, or when the object passing un-even surface.

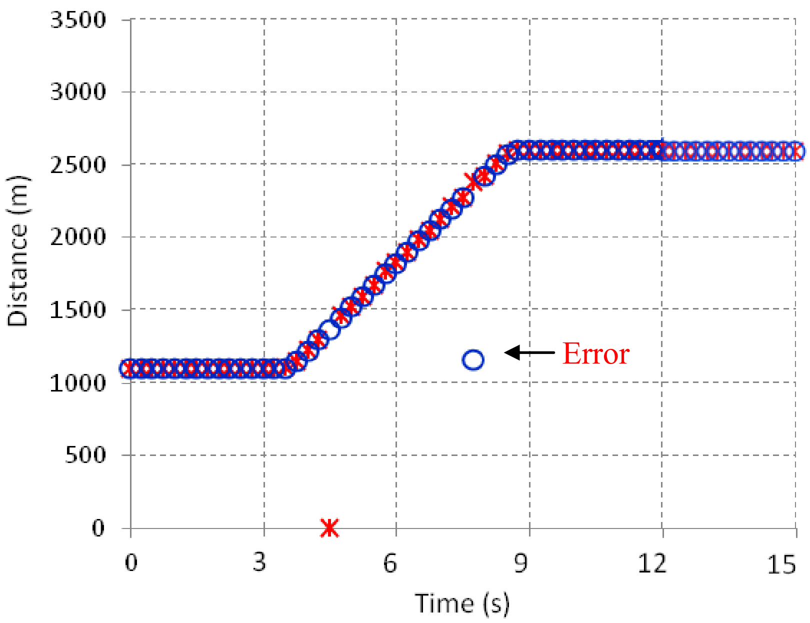


Figure 4.11. Wrong estimation of Doppler shift that leads to inaccurate distance estimation.

Actually, due to symmetry property of power spectrum calculation, Doppler shift can be detected from the frequency change at around 36 and/or 60 kHz (Fig 4.12c). Sometime at one frequency the peak is higher and more visible than other as shown in Fig. 4.13. Therefore, there is also an alternative method for Doppler shift detection by observing frequency shift at those two frequencies. It may give better result. However it will increase the computation complexity and hence careful consideration is needed before selecting this option.

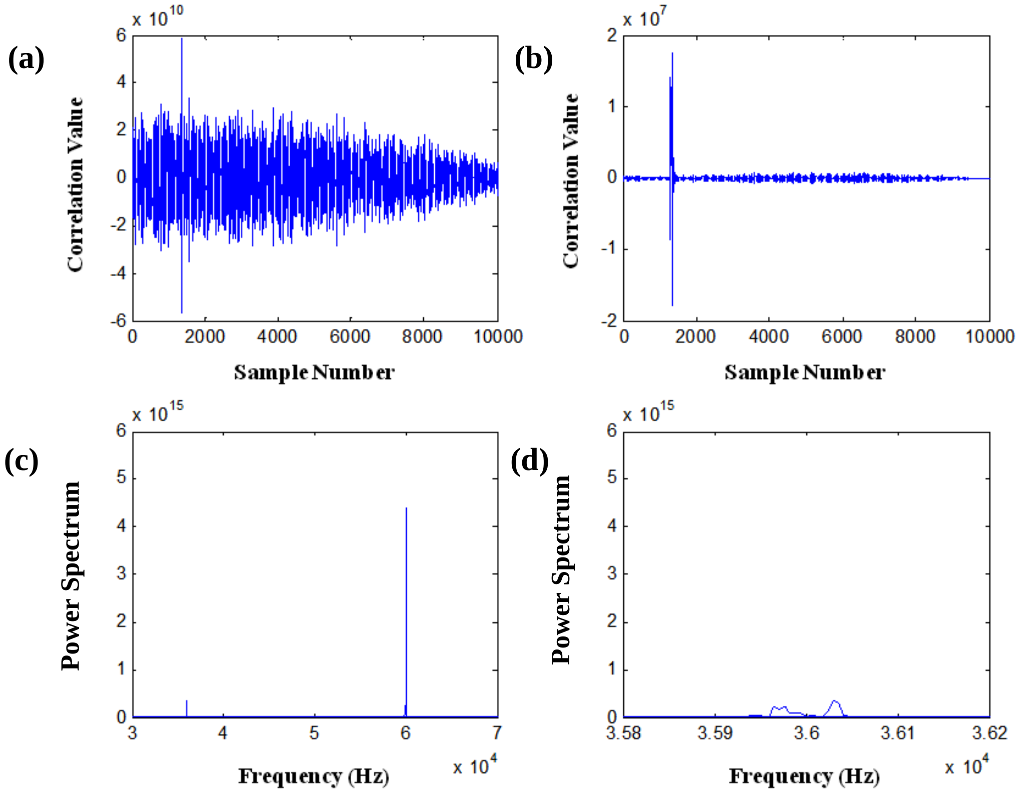


Figure 4.12. Correlation and Doppler shift estimation for experiment shown in Fig. 4.11.

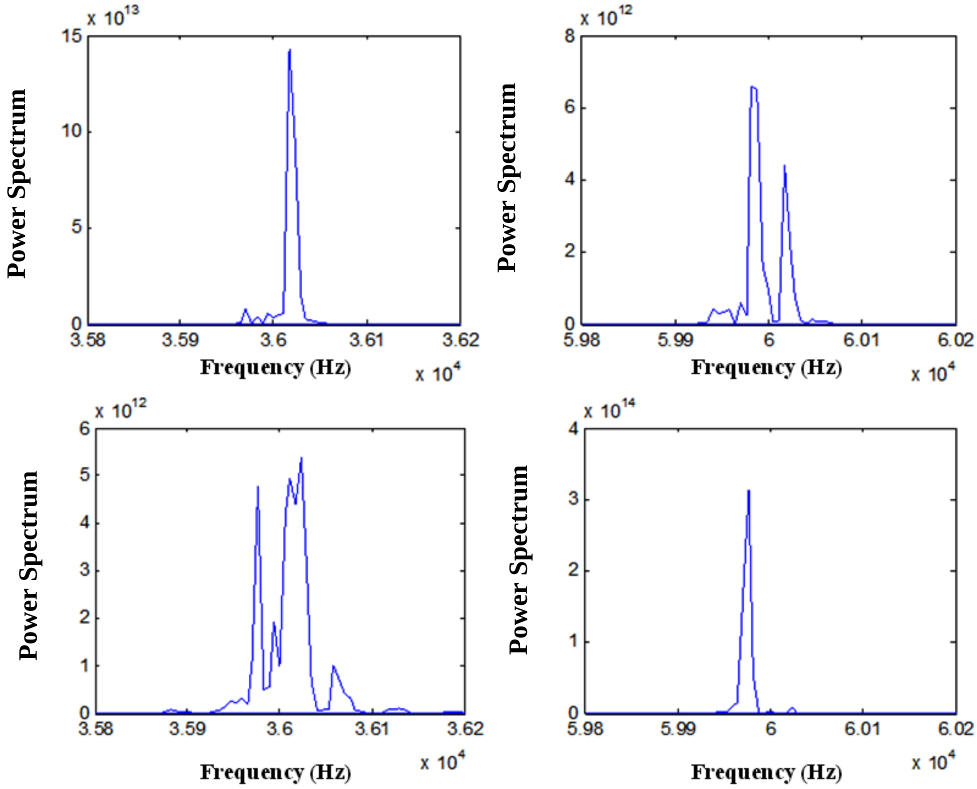


Figure 4.13. Power spectrum at 36 kHz and 60 kHz for detecting Doppler shift.

4.5.2. Moving object localization test

The localization results for an object moving in a circular path at various angular velocities are shown in Fig. 4.14. Generally, the position was accurately estimated. No performance degradation was observed, even when the object was moving at a relatively high speed (1.3 rad/s). However, there was an issue with regards to outliers. An occasional incorrect measurement was obtained, presumably due to a disturbance, such as reflection, interference and so on (see Fig. 4.14). Further analysis showed that this problem was generated by erroneous distance measurements. Figure 4.15 shows a profile of the measured distances to the node 3, where erroneous distance measurements were observed.

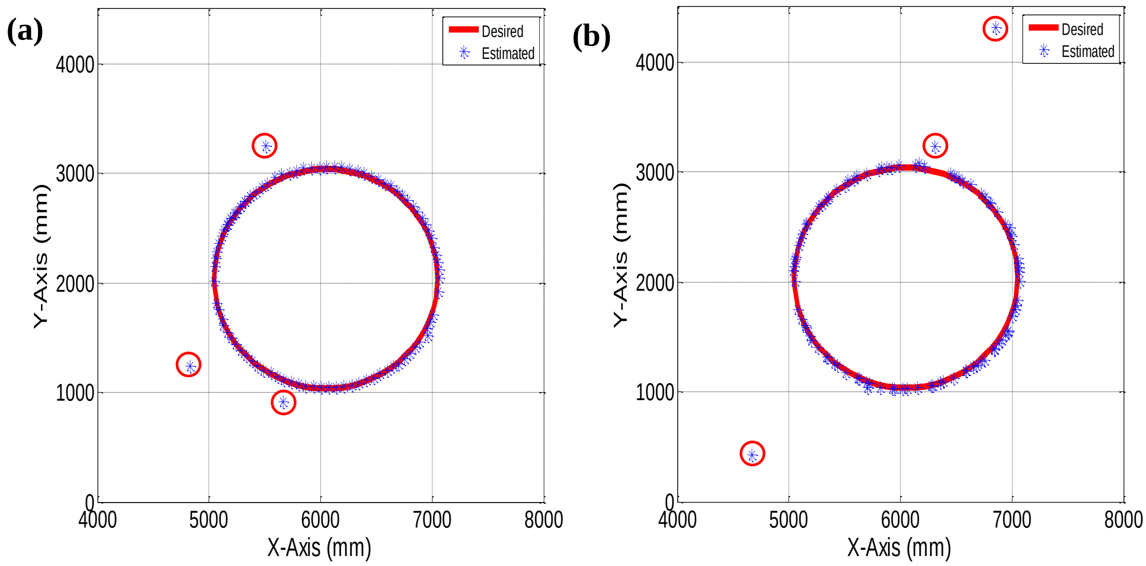


Figure 4.14. Examples of outlier (marked with red circle) as the result of inaccurate distance measurement: (a) ω = 0.3 rad/s and (b) ω = 1.3 rad/s.

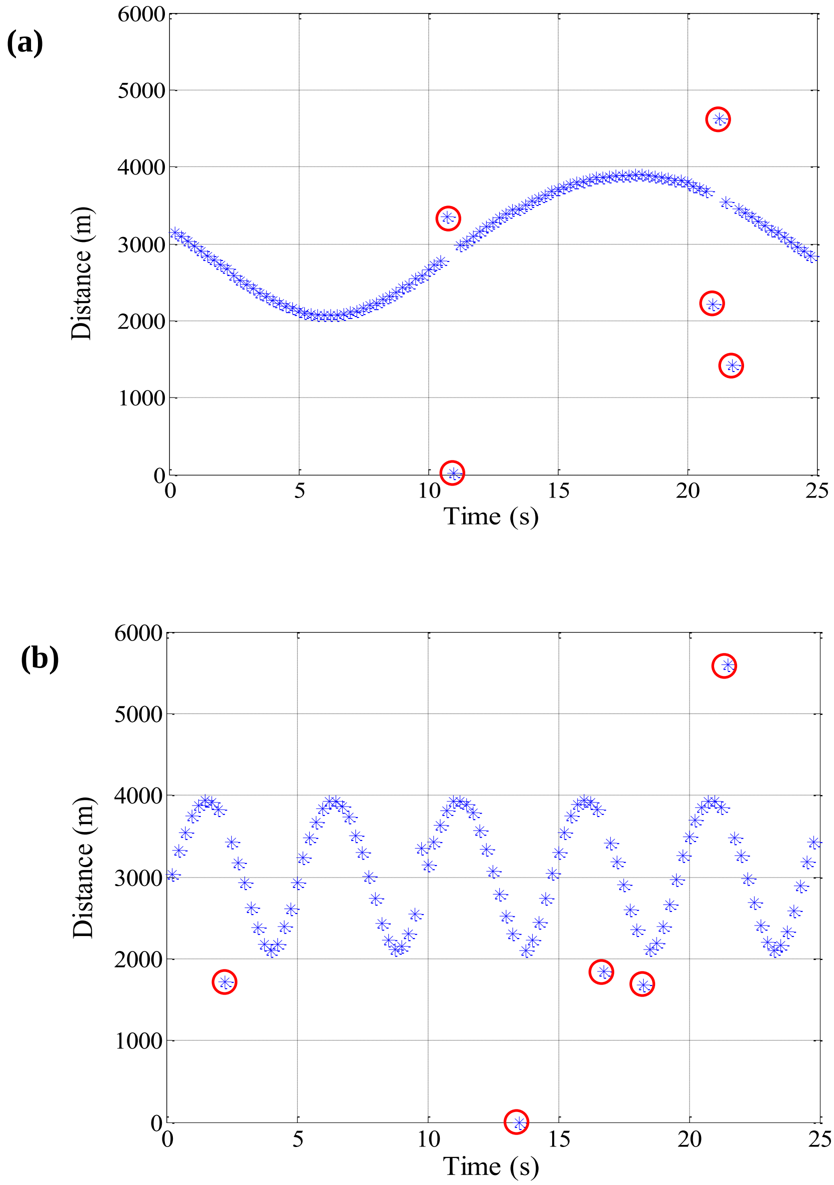


Figure 4.15. Examples of wrong distance measurements (marked with red circle) at different angular velocity: (a) ω = 0.3 rad/s and (b) ω = 1.3 rad/s.

This problem was also seen in other development systems [21, 25]. To overcome this problem, outlier rejection is necessary, regardless of the cause. We implemented an outlier rejection procedure as follows:

1). Get the current distance from the speaker to each fixed microphones (nodes): $d_{m/k} = [d_{m1/k}, d_{m2/k}, d_{m3/k}, d_{m4/k}]$ and Doppler-shift $\Delta f_k = [\Delta f_{1/k}, \Delta f_{2/k}, \Delta f_{3/k}, \Delta f_{4/k}]$.

2). Estimate the velocity the object is moving towards or away from each microphone $v_{m/k} = [v_{m1/k}, v_{m2/k}, v_{m3/k}, v_{m3/k}]$ using the following equation:

$$\Delta f_{i/k} = \left(\frac{v_s}{v_s - v_{mi/k}} - 1 \right) f_0 \tag{14}$$

where f_0 = 36 kHz and vs is the speed of sound (in m/s), which depends on temperature T (^{o}C) as follows:

$$v_s = 331.5 + 0.61T \tag{15}$$

3). From the previous valid distance $d_{m/k-1}$ and $v_{s/k}$, the predicted distance at the next time step $d_{m/k}^* = [d_{m1/k}^*, d_{m2/k}^*, d_{m3/k}^*, d_{m4/k}^*]$ which can be estimated using a kinematics model:

$$d_{m/k}^* = d_{m/k-1} + v_{si/k}\Delta t_s \tag{16}$$

where Δt_s is sampling time.

4). In order to validate a new data point, a standard deviation of measurement error associated with each fixed microphone (σ_i) is set, and the measured distance ($d_{m/k}$) is compared with the predicted distance ($d_{m/k}^*$) . If $d_{mi/k}^* \pm 5\sigma_i \leq d_{mi/k} \leq d_{mi/k}^* \pm 5\sigma_i$ then $d_{mi/k}$ is a valid value, otherwise it is considered an outlier and rejected.

Note: The value of σ_i is obtained from measurement results in previous research. Here, the tolerance value is set to ±5 σ_i to moderate outlier rejection (statistically, for normally distributed data 99.7% of data will fall in the range of $d_{mi/k}^* \pm 3\ \sigma_i$).

5). To estimate the position of an object in 3D space, three or more valid distances are required. Therefore, after validating the measured distances, if the number of valid distances ≥ 3 then the position of the speaker is updated. Otherwise the update is postponed until the required number of valid distances can be obtained.

Figure 4.16 shows localization performance after implementing the outlier rejection procedure. In these figures only the data of estimated position for one revolution are shown. Despite, the performance was evaluated from several revolutions data. For real life navigation of autonomous vehicles this system can be combined with an odometer to provide additional information to validate and determine position in between data updates. Thus, data gaps, due to outlier rejection, can be accommodated. This approach is also widely used for GPS-based navigation system e.g. the system used in [34].

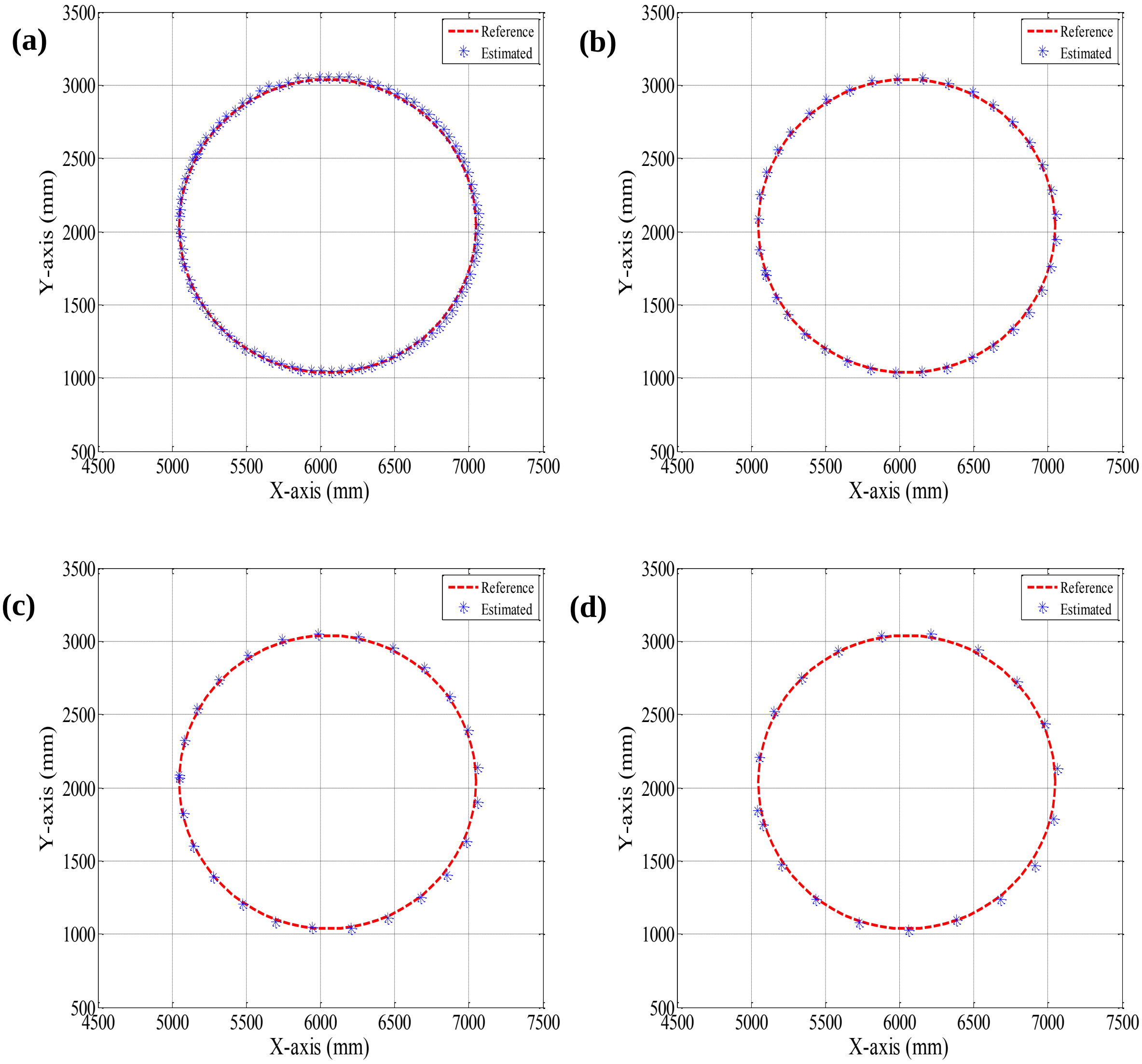


Figure 4.16. Localization of an object moving in a circular path with variable velocity: (a) 0.3 rad/s, (b) 0.7 rad/s, (c) 1.0 rad/s, and (d) 1.3 rad/s.

Position errors relative to object moving speed are shown in Fig. 4.17. Where ω was between 0.3 – 1.3 rad/s, the position error was around 20 mm. This performance is better than that reported in another experiment [28]. Even for faster moving objects, the measured errors were smaller than that previously reported. Beside the advantage of using a spread spectrum approach, the main reason for this difference in performance was related to the system configuration. In that previous report, they used a GPS configuration (passive mobile system), while in our system we used an inverse-GPS configuration (active mobile system). The main limitation of passive systems for localization of a moving object is that simultaneous measurement of distance cannot be guaranteed [21]. Usually, the distances are measured one at a time, in between measurements the object has moved on from one measuring point to another. As a result, there is a high dependency between positioning accuracy and object moving speed. The faster the object moves the more positioning accuracy deteriorates.

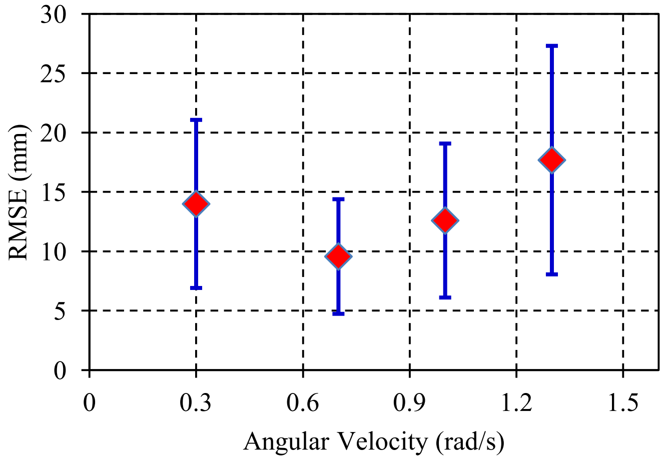


Figure 4.17. Relation of angular velocity of moving object and the localization error.

In [28], two different frequencies were used for the ultrasonic positioning system. This system has both the advantage of a faster measurement time and minimized problems with simultaneous measurement. However, because four beacons were used it means that two successive measurements were still needed to get all four distances, thus the problem of simultaneous measurements is retained. This could contribute to increased position inaccuracy in such a system as the angular velocity of the object increases.

An active system does, however, have its limitations. There is a problem related to network infrastructure as the number of mobile station increases and also a privacy issue [21]. This, however, is not an issue here because the system is used for navigation or other possible applications with limited numbers of mobile stations. In any event, privacy may not be a critical issue for those applications.

Another important issue is related with the possibility of performance degradation for application at wider area and at higher moving speed. Even though performance evaluation of the proposed method was conducted in relatively small area, the obtained results show that the accuracy of moving object localization is close to the accuracy of distance measurement. Based on this result and also the results from our previous work [27], the proposed method is expectable to work well at wider area without significantly decreasing the performance. In respect to moving speed, there is no clear trend from the plot shown in Fig 4.17. However, considering high accuracy at the current highest speed (~1.3 m/s), it is plausible that the proposed method also has possibility to be applied at higher speed. Indeed, the speeds used in this experiment are sufficient for general agricultural application and therefore may not be a critical issue here.

4.5.3. The influence of wind

There are two factors related to the influence of wind investigated here, wind speed and its direction relative to the object movement. Experimental results for different setup are shown in Fig. 4.18 and Fig. 4.19. About the influence of wind speed, the experimental results showed that for all cases more fluctuation on correlation SNR was observed under the influence of higher wind speed. Figure 4.18 shows the results when speaker moves toward microphone. Once the speaker gets closer to the microphone, the sound level increases and hence, in case there is no influence from other factors, high correlation value will be observed. However, the presence of wind will also affect the sound propagation. In this experiment the wind was generated using electric fan and it was inconstant. Therefore it may generate some fluctuation as observed in the results. The obtained results was combination of these two effects (i.e. the increasing of sound level and the fluctuation caused by wind). As the wind speed increase, the fluctuation shows more significant effect than improvement of sound level, yielding more fluctuate and lower correlation values.

Wind direction also affects the correlation value, although it may not as significant as the wind speed. It was observed that when the wind moves toward microphone the correlation value was less affected than when it moves away. As expected the worst result was observed when both the speaker and the wind direction move away from the microphone (Fig. 4.19d). These results may also have some relation with previous report [35]. In their work they showed that the power spectrum of sound wave will be spread in broader range under influence of higher wind speed. However, further investigation is needed to confirm it. Even though the experimental results showed some influence of wind on the correlation value, it was also confirmed that at tested wind speed (i.e. up to 5.6 m/s) the sound wave is still can be well identified. Hence, it can be expected that the proposed Doppler shift compensation method can work well under influence of similar condition in real field. Further investigation is also necessary to determine the actual limit of wind speed that still can be handled without decreasing the performance.

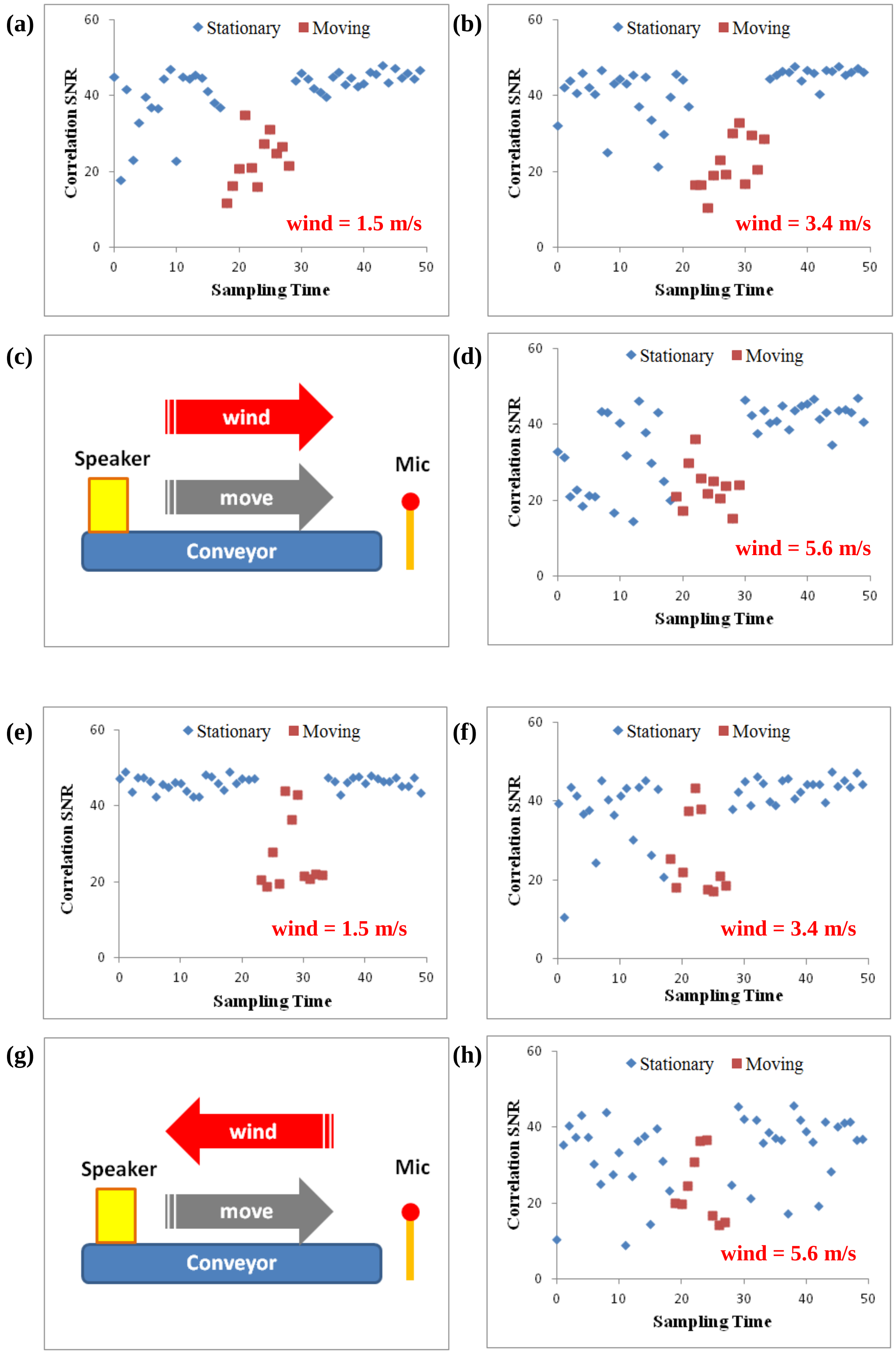


Figure 4.18. The influence of wind with variable speed and direction (relative to microphone) on correlation value when speaker moves toward the microphone.

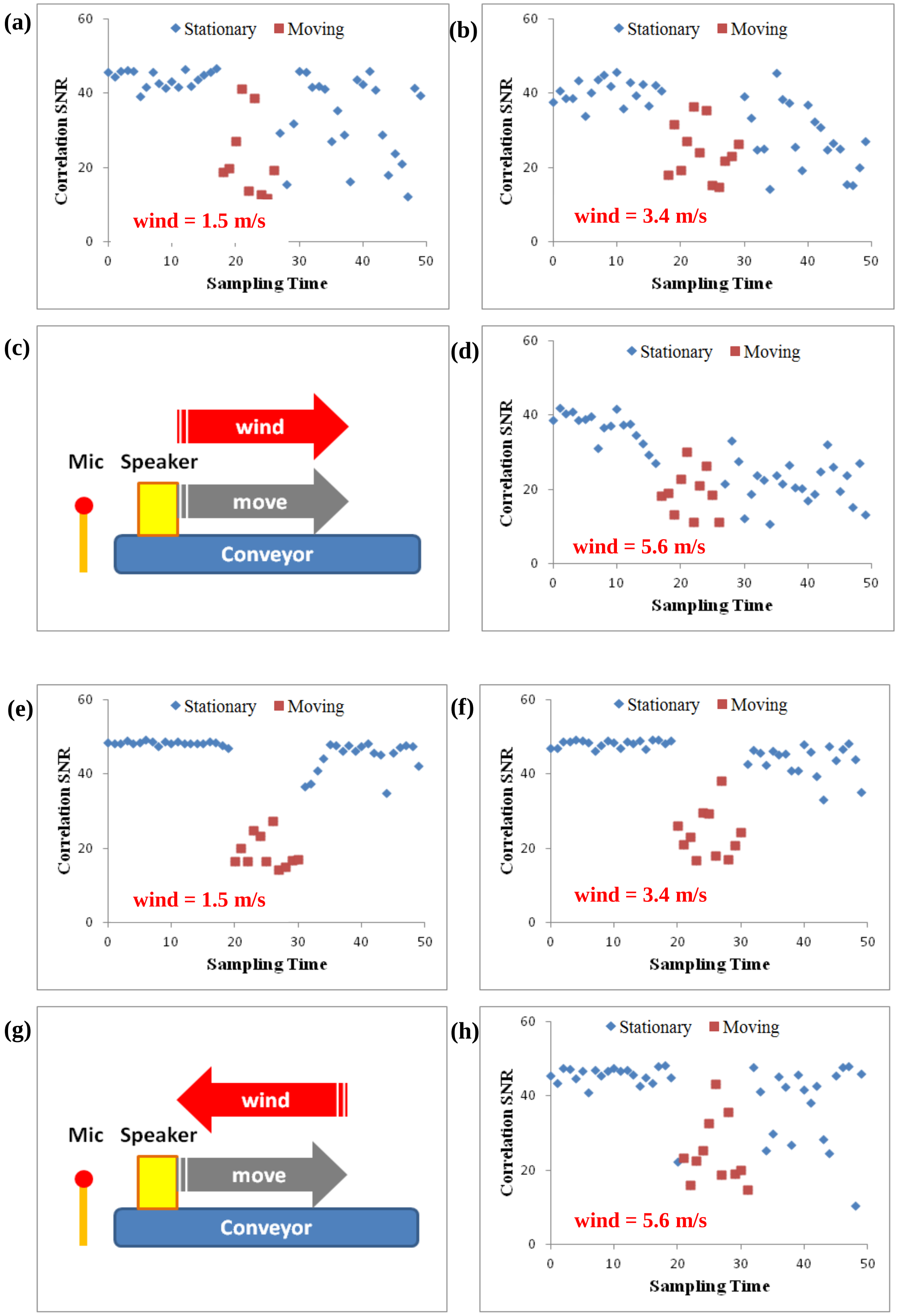
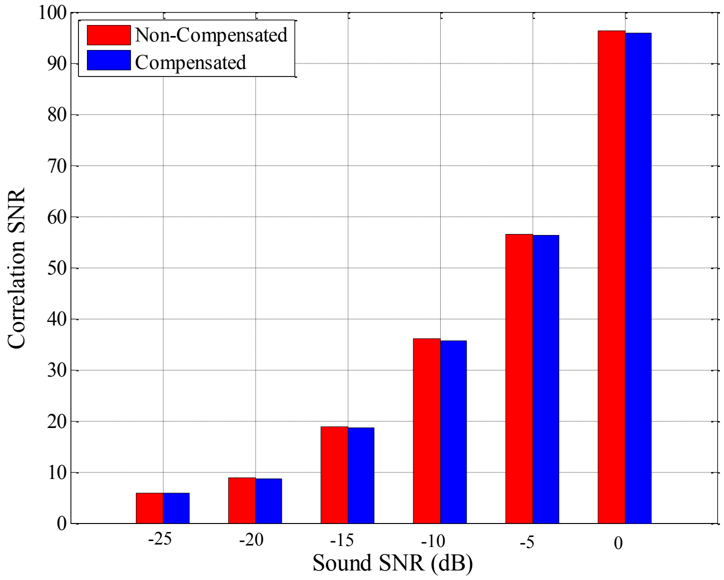


Figure 4.19. The influence of wind with variable speed and direction (relative to microphone) on correlation value when speaker moves away from the microphone.

4.5.4. The influence of noise

For real life applications in agriculture, background noise is likely to be present. Intense noises may come from a variety of sources, especially agricultural machinery [36]. Thus, it is necessary to evaluate the performance of the proposed method in the presence of noise. We tested localization performance at various noise levels (i.e. at variable sound SNR values) ranging from 0 to -30 dB. We also compared the performance for both stationary and moving objects.

(a)



(b)

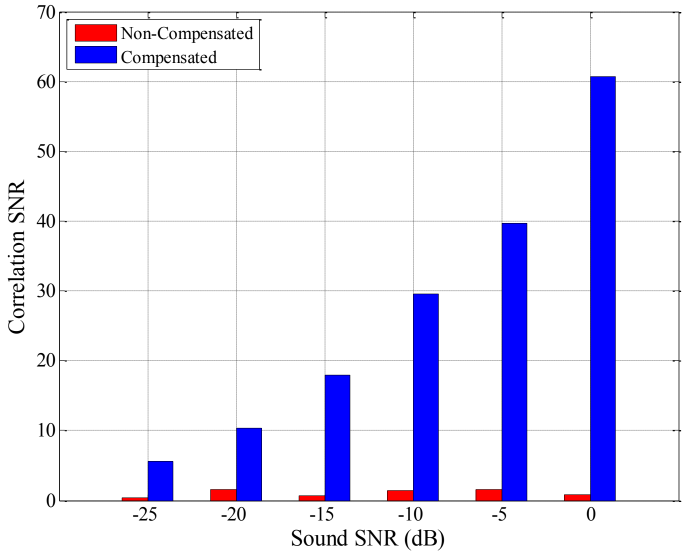


Figure 4.20. Correlation SNR for compensated and non-compensated system: (a) Stationary. (b) Moving object (0.2 m/s).

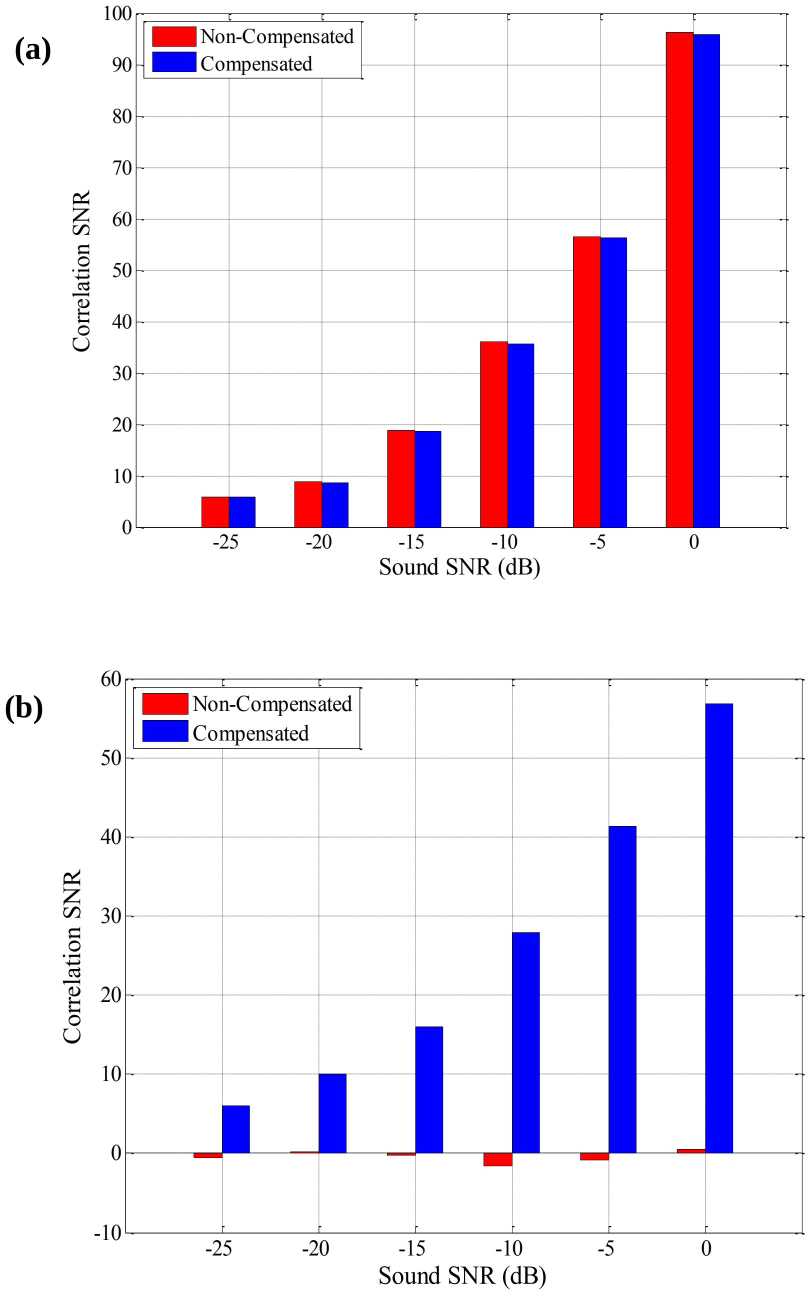


Figure 4.21. Correlation SNR for compensated and non-compensated sytem: (a) Stationary. (b) Moving condition (0.8 m/s).

When the object was stationary (Fig 4.20(a) and Fig 4.21(a)), the object could be accurately localized, with or without compensation, up to a -25 dB noise level. Clear identification of the signal was achieved as the high correlation SNR indicates. However, for a moving object (Fig 4.20(b) and Fig 4.21(b)), for the non-compensated system there was a very low correlation SNR. On the other hand, although there was some decrease in the correlation SNR for the compensated system compared to when the object was not moving, it still accurately localized the moving object. This indicates that the presence of background noise did not significantly interfere with the performance of the system with Doppler shift compensation. The background noise limit that the system could tolerate was -25 dB. Beyond this value, interference to the system was too large, regardless of whether the object was stationary or moving.

4.6. Conclusions

This paper evaluates an alternative solution for localizing a moving object by using a spread spectrum sound-based positioning system with Doppler shift compensation. By taking advantage of a spread-spectrum approach, which is capable of precise distance measurements, and an active mobile architecture, experimental results demonstrate that the proposed system can achieve high positioning accuracy. In this work the system was tested at variable speed with maximum speed 1.3 m/s. This speed is sufficient for general application agricultural operation. It is also much higher than that used in other previous works. Further study is required to evaluate the actual speed limit that can be handled. Investigations also indicate that the proposed system can tolerate background noise up to -25 dB without compromising accuracy. The experimental results also showed that the proposed compensation method also works well under influence of wind up to 5.6 m/s. However, similar to the object speed, further investigation is necessary to determine the maximum limit of wind speed that still can be handled. To further improve the current system, estimation of the position using filtering methods, such as a Kalman filter or a particle filter, could be investigated.

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Chapter 5

*Self-calibration Method of Spread Spectrum Sound-based Positioning System: An attempt to scale up the system**

Summary

Extensive researches on development of sound-based positioning system have been conducted in the recent years. Sound-based positioning system is considered as a good alternative of well known GPS system, especially for indoor environment. It can provide high positioning accuracy with relatively low cost. There is also a potential to use it as a low cost platform for automation and robotics system in agriculture.

Recently, we have developed a spread spectrum sound-based positioning system. The selection of spread-spectrum sound, instead of ultrasound which is popular and widely used, is due to some characteristics that make it more suitable to be used for agricultural setting. It has high noise tolerance property and also gives a possibility to apply Code Division Multiple Access (CDMA) which can significantly improved the performance especially in term of processing time. Despite of the additional noises that may be generated and considered as a drawback of this system, it is considered to be more appropriate for this work.

Development of sound-based positioning system in agricultural area is a challenging task. There are many factors need to be taken into account such as the influence of wind, temperature gradient, the presence of obstacles, and also background noises. In previous work, we try to address some of those issues. We also tried to extend the work not only for estimating position of a still object but also for a moving object.

**Full version of this chapter has been submitted for publication*

In this chapter, we would like to address another important issue related to deployment of the system. During the deployment stage, it is required to set several fixed nodes at known positions. This process is known as *calibration*. In conventional way, it is done by manual surveying using theodolite/total station. This kind of task is laborious, impractical, time consuming, require special skill and devices which are also expensive. Therefore, self-calibration method that automatically calibrates the system is demanded.

It is also important to scale up the system into wider working area. The coverage of such kind of system is relatively small, for the developed system it is only effective for a 40 m x 40 m area. Hence, scaling up the system is an important issue need to be resolved. There are some related researches have been done to address this problem. Compared to other methods, the unique point of this work is that the proposed system configuration also takes into account about wind compensation. In previous work, we showed the possibility to minimize the negative influence of wind by using base/reference station method. The additional base station, set at known position, is used to estimate the sound velocity more accurately. By introducing such compensation method, the positioning error was greatly reduced.

To enable self-calibration, the basic configuration of spread spectrum sound-based positioning system was modified. Actually, it can be applied for either GPS-like or inverse-GPS system. However, here we used inverse-GPS system. In the new setup, five omni-directional speakers equipped with microphone are used as Base Stations (BS). Using this setup, distance measurement from one BS to others can be conducted in two directions to improve measurement accuracy. These distance data are then used as the basic information to perform self-calibration.

In principle, self-calibration is about keeping the balance between number of unknown variables in certain location system, and the set of available distance measurements data. It is necessary to make the system *fully* or *over determined*. It can be achieved by constraining the location of mobile unit during the self-calibration process or by taking some simplification to reduce the number of unknown. Using the proposed configuration, overall there are 10 distance data and 15 unknown variables (i.e. three coordinate variables for each BS). Using some simplification by locating three BS at $(0, 0, h)$, $(x_2, 0, h)$, and (x_3, y_3, h), where h is pre-defined height of BS; leaving nine unknown variables. Hence, the system becomes over-determined. The position of each BS then can be estimated simultaneously by solving a set of equation system. In this case iterative least squares method was used as solver.

Alternatively, instead of simultaneous approach, we split the system into several triangular shapes and perform step-by-step calibration for each of them. Briefly, this procedure can be explained as follows: (1) Starting with the first triangle, there are three obtained distances data and nine un-known (i.e. three coordinate variables for each BS). Using the same simplification as discussed above, we can reduce it into three un-known only. Thus, it becomes a fully determined system that can be solved easily (2) Using two of BS coordinates obtained in previous step then coordinate of other BS can be estimated with similar approach and this step is repeated until all un-known variables are solved.

Experiment and simulation were performed to evaluate the proposed system. The experiment was conducted in greenhouse at National Institute of Vegetable and Tea Science, Aichi, Japan, on the last summer (August 2012). This setup is selected, instead of outdoor experiment, to enable investigation of the effect of influencing factors especially wind and temperature to the calibration performance. In this experiment the self-calibration method was tested in two ventilation windows settings: open and close. The main purpose of this setup is to evaluate the influence temperature and wind on the calibration performance. For each setup, position of each BS was calculated using self-calibration. It is then compared to the actual position obtained from manual calibration using total station to evaluate the error.

After finishing self-calibration process, we also conducted numerical simulation in Matlab to compare the localization performance of self-calibrated and manually calibrated system. There are 10 test points to be localized. For each point, localization was repeated 50 times. To simulate a realistic condition, we randomly added measurement error obtained from our previous experiment (average: 20.67 ± 4.66 mm). Here, the evaluation was based on positioning error in 2D.

The experimental results indicated that the second approach (i.e. solving the set of equations partially, step by step using triangular shape) is more robust than the first approach that tries to find all unknown variable simultaneously. Unlike the second approach that in some cases fails to converge into a good solutions, the first approach always come with solution because it is based on fully determined system. However the accuracy strongly depends on the quality of distance measurement data for each segment. Also inaccuracy at each segment will be carried on and accumulated. Despite of this limitation, it was selected to be used and all results presented and discussed here were based on this approach.

Experimental results showed that using the proposed self-calibration method all BS could be localized within 5 cm error in 2D. However, as discussed before performance in 3D is relatively low due to the poor distribution of BS in the *z*-axis. Considering calibration results of four BS which are later used for object localization only, it showed that the self-calibration still could achieve a good accuracy. All BS also could be localized with accuracy of 2-5 cm. It is similar to the localization accuracy using the developed positioning system. It is also comparable with reported results of some previous works.

The results also indicated that self-calibration for open condition is slightly better than close condition. There are some possible reasons for this but basically it is related with inaccuracy of the speed of sound wave used in the calculation. The speed of sound is affected by temperature, pressure, relative humidity and the constituents of the air. Because the experiment was conducted in greenhouse and the open condition showed better results, temperature and humidity are considered as the most influencing factors that affect the performance. For the close condition, the wind is relatively low and stable. However the temperature rapidly increases, especially during summer (when the experiment was conducted). This rapid change will affect the sound velocity, yielding inaccurate distance measurement and finally decreasing the calibration performance. For outdoor, it may be a different situation. Although there is also temperature gradient that may influence the sound propagation, the main challenge may come from wind. Therefore it should be taken into account when the proposed self-calibration method is intended to be used for outdoor.

Further simulation results showed that the error of position estimation using self-calibrated system is higher than that using manually calibrated. For self-calibrated system, the positioning error is 47.4 mm (2D) and 147.0 mm (3D). Almost twice of that using manually calibrated system that is 20.3 mm (2D) and 79.2 mm (3D). Although the positioning accuracy using self-calibrated system is slightly worse than those using manually calibrated system, it is still sufficient for some practical uses, especially when inaccuracy along the z-axis can be tolerated (i.e. when the floor is relatively flat). This result also gives guidance for selecting proper calibration method in practice. For fine grained system which requires high accuracy, manual calibration is maybe more suitable. However, for moderate system, self-calibration may be preferable.

The results indicated the feasibility to apply the proposed method to calibrate BS position with reasonable accuracy; however it is important to find alternative ways to further improve the performance especially for 3D case. The use of other solver such as different approach of least squares method or simulated annealing may be a good alternative. Another things that need to get more attention is about unification of coordinate system. In many works, due to limitation of the system (e.g. maximum range can be reached) or other constrains (e.g. separated room), the self calibration is only applied in small area. Therefore, combining self-calibration results of several small areas with arbitrary coordinate space into single, unified space is also an important direction for further research.

Chapter 6

Conclusion and Future Work

6.1. Conclusion

Along with arising concern on the practice of precision farming and development of automated system, positioning system will be one of supporting technologies that plays an important role in current and future agriculture practices. In recent years, GPS has been widely used and adopted. Despite of the advance development and high performance of GPS that well match with requirement of wide range of applications, many researchers also put much attentions and efforts for finding an alternative positioning system especially for reducing the cost and as alternative when GPS does not work e.g. at indoor environment. In this study we demonstrated the feasibility to develop an alternative low cost positioning system using spread spectrum sound. It is also a promising potential to use it for supporting various agricultural operations that require position information. The following are main findings obtained from this work followed by a brief discussion.

Chapter 2 gives a brief description of the developed sound-based positioning system. Here, spread spectrum approach was used to generate sound wave. This approach is considered to be more suitable for agricultural setting. It can provide high accuracy [1] and less suffering from the interfering of various noises [2]. It was also developed using components of audio system which are readily available in the market. Hence, it can be developed with relatively low cost [3]. The basic performance of the developed system has been assessed through experiment. In this case distance measurement as the basic of positioning system was conducted as basic assessment. It was confirmed that in average the developed system was capable of measuring the distance of 10 m with an accuracy of 3.5 -7.1 mm, depends on the sampling frequency used for acquiring the data [4]. Another important note is about selection of frequency of carrier wave. In this work, frequency of 24 kHz was deliberately selected. This frequency is the center of the generated sound signal. Due to the property of spread-spectrum technique, part of the generated sound was in the range of audible sound (within 20 Hz – 20 kHz) which may be considered as noise and inconvenient for users. However, it is some kind of trade-off. The low frequency wave gives great distance and advantage on handling obstacles [5-6]. In the other hand, high frequency wave gives higher accuracy without generating noises (when the selected frequency > 20 kHz) [6]. Another consideration is about noise from other machine that may interfere and affect the performance of the system. Investigation showed that noises generated by agricultural machineries are typically in low frequency. Considering all of those factors, then 24 kHz carrier wave was selected.

Chapter 3 discusses about reduction of negative effect of influencing factors which is one of key issues on developing accurate sound-based positioning system. One of those issues is wind which significantly affects the performance especially for outdoor setting. In this work, alternative wind compensation method using base station was proposed. Experimental results confirmed that the proposed method can greatly improve the positioning accuracy. The results also suggested that using base station set at the center of working area could give better performance of wind compensation. Despite of improvement that can be achieved using the proposed method, some challenges still remain. The most important issue is about limited update rate. In the proposed method, multiple access technique is required and after some experiments and evaluations, Time Division Multiple Access (TDMA) was selected. This technique could work well for wider area and less suffering from problem related to misdetection of sound wave. However, using this technique processing time become longer and yield low updating rate. In current system the update rate is 2 Hz which is in-sufficient for some applications. To solve this issue the use of other sensors through fusion approach may be a good alternative.

Chapter 4 describes an effort to address the next challenge related to Doppler's shift problem. This problem is associated with object movement. When an object is in motion, due to Doppler's effect the frequency of sound wave used for positioning will change. It will cause a problem on signal detection, yield in decreasing positioning accuracy. The proposed compensation method used additional sound wave to detect the Doppler's shift and then use it to adjust the signal detection process accordingly. The performance of the proposed method was verified through experiments. The results showed that it could effectively used to maintain the positioning accuracy of an object moving at variable speed 0 -1.3 rad/s (~ 0 – 1.3 m/s). Although further investigation is needed to determine the actual limit of speed in which the proposed method still works well, the results outperform the similar work reported in [7], even though in this work we used higher speed. The proposed method also works well even under the influence of wind and noises. It also can be concluded that for application that require high mobility, inverse-GPS setup (also known as active mobile setup) is more preferable than GPS-like system. The guarantee for simultaneity of distance measurement is the most important reason for this. This property is also the main reason, beside improvement from the proposed Doppler's shift compensation, for the excellent performance of moving object localization presented in this thesis. Of course there are limitations of this setup especially the need of infrastructure for communication when it is scaled up and privacy issue as mentioned in [1]. However, those issues may not be a serious problem for agricultural applications. There is no privacy issue and also unlike other area that needs to deal with many devices, in agricultural application there is only limited devices used.

Chapter 5 explores the possibility to use self-calibration method for easy deployment of the proposed positioning system. It is still in very early stage of development. However, it can be considered as a first attempt to scale up the proposed system into wider area. The unique point of the proposed self-calibration method which make it differs from other related works is that it put into account wind compensation method as described in Chapter 3. From the experiments, it was realized that the proposed method could perform calibration quite well especially for 2D case. In case of 3D the performance was low due to poor distribution of fixed nodes in the z-axis that yields poor Dilution of Precision (DOP).

Look at the overview of the desired system as introduced in the beginning of this thesis; we realize that only a few aspects of development of sound-based positioning system covered here. There are still many challenges and works to be done to actually realize the proposed system as an alternative low-cost positioning system. However, what have been achieved at this stage can be considered as one step ahead for achieving that goal.

6.2. Future Work

There are many aspect of development of sound-based positioning system in agricultural area that still un-explored. This section tries to give some prospective directions on further improvement of the current system as well as other related aspects.

6.2.1. Further prospective improvement of the current system

- *Mitigation and compensation for multipath problem*

The presence of obstacles such as plants, building structures, human is another important issue that needs to be addressed. In previous work we also tried to address this issue, by introducing ANN-based prediction model for the error caused by multipath effect [8]. Although it could give some improvement on range measurement accuracy, better solution is needed. Actually there are many solutions, for mitigation and error reduction, have been proposed in previous works [5, 9]. However, condition of agricultural setting is much more complex, more obstacles with different shape and size need to be handle. Hence, there is no guarantee that those alternative solutions can be applied effectively. Further investigation is necessary to find better solution.

- *Near-far problem associated with CDMA*

As discussed in chapter 3, there is a so called near-far problem associated with CDMA. It is considered as drawback of this multiple access technique. This problem strongly influences the detection of sound that in worst case may leads to the failure to obtain position information. In the other hand, it can greatly save processing time. This advantage point will be more visible for GPS-like system where multiple speakers used. In this case the use of TDMA no longer applicable because it will takes much more time. One possible solution to solve the near-far problem is by using interference canceller which is popular in the area of communication system e.g. the methods proposed in [10-11].

- *High humidity issue especially for greenhouse application.*

Humidity is another influencing factor that needs to be considered especially for application in closed environment such as greenhouse. The influence on the sound wave itself may not as significant as other factors e.g. temperature; however it strongly affects the performance of wireless device. High humidity greatly reduces the effective reachable distance. Wireless device is important component of the proposed sound-based positioning system especially related to practical and scalability issue. Hence further investigation and also alternative solution to overcome this issue is also important to be done.

- *Scaling up issue*

Scalability issue is one of major issue for many alternative positioning systems (i.e. other than GPS). This problem arises mainly due to coverage area of those alternative systems is typically small and hence it needs to be scaled up. Many reports have been proposed to solve it e.g. [12-14]. In this thesis, we also proposed an alternative solution for this issue. However as discussed before, the performance is still low especially for 3D case. Therefore, it still becomes an open problem to solve.

6.2.2. Possible applications

Another interesting topic is about development of practical application using the developed positioning system. Basically, this system can be used in various applications that currently use GPS. However, due to limitation of the current system especially related to coverage space which relatively much smaller and also low update rate, further consideration and adjustment may be necessary. One possible application is development of navigation of autonomous vehicle or mobile robot.

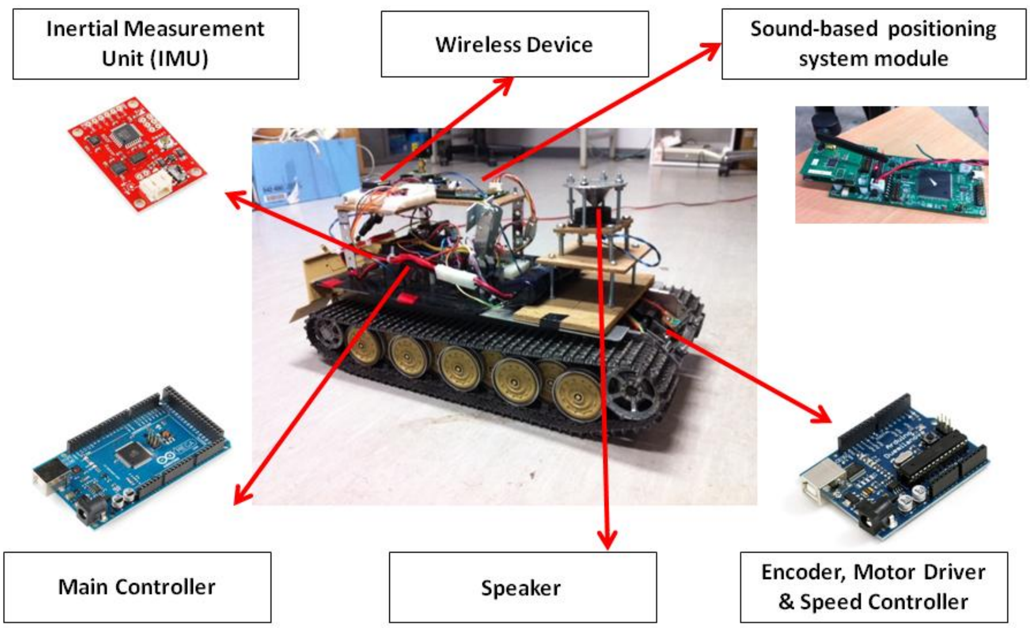

Figure 6.1. Example of mobile robot equipped with various sensor and use sound-based positioning system for navigation.

For such kind of application, update rate is a critical issue. The update rate of the currents system is 2 Hz. It is much lower than typical GPS which has update rate of 10 Hz. Therefore, the use of other sensors such as encoder and inertial Measurement Unit (IMU) is likely a mandatory. Using those additional sensors and sensor fusion approach, the position update rate issue can be resolved. Figure 6.1 shows example of mobile robot equipped with sound-based positioning system module and other sensors that used in on-going research by our group to demonstrate this feasibility.

There is also a possibility to use the developed positioning system to extend the work reported in [15] to construct virtual low-noise space in noisy environment. Using the proposed system, they tried to facilitate the communication among operators who working in noisy environment as if they are in a low-noise environment. It was done by reducing the noise using noise-cancelling headphone and creating communication system based on audio image which is recreated on the basis of operator’s mutual position. Therefore, recognition of operator’s position and heading become one of key component of the system. In their work they used TV camera installed on the ceiling to monitor operator’s position and heading. The limitation of this monitoring system is the small coverage area. In this case the developed sound-based positioning system can be used to replace it to get wider coverage.

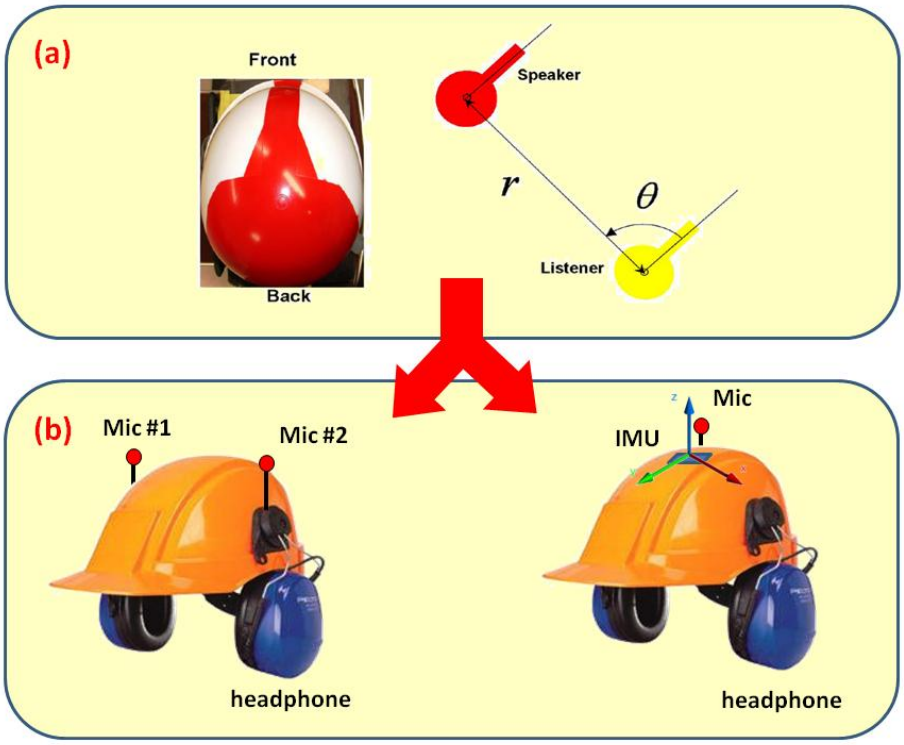

Figure 6.2. Operator’s position and heading recognition using (a) TV camera and (b) sound-based positioning system.

For this application GPS-like setup is likely more appropriate. To determine operator's position and heading at least it can be done using two approaches as illustrated in Fig. 6.2. First using two microphones mounted on the operator's helmet or hat. Position and heading of the operator can be calculated by using position of these microphones position. Alternatively it can be done using single microphone combined with IMU to obtain the heading. Further analysis including system complexity as well as cost analysis is necessary to see the feasibility to use such approach and also to determine which approach that actually more suitable.

6.2.3. Economic analysis

The possibility to be used as an alternative accurate yet low cost positioning system maybe is the main promising aspect of the developed system. However, more detail economic analysis is necessary to assure. The most important issue is about the optimum scale of the working area. Intuitively, the developed system may be suitable for relatively small area e.g. for Asian style farming. Compared to GPS, economically it will be much more effective. For large scale application, however, it may be totally different condition. GPS may be much more effective. The economic analysis will give clear guidance for selecting appropriate positioning system for certain application that will give maximum benefit.

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